LEADING THE ENERGY TRANSITION

FACTBOOK

Electricity Storage

SBC Energy Institute

September 2013

Schlumberger | SBC Energy Institute

Compiled by the SBC Energy Institute

About SBC Energy Institute

The SBC Energy Institute, a non-profit organization founded in 2011 at the initiative of Schlumberger Business Consulting (SBC), is a center of excellence for scientific and technological research into issues pertaining to the energy industry in the 21st century. Through its unique capability to leverage both Schlumberger's technological expertise and SBC's global network of energy leaders, the SBC Energy Institute is at the forefront of the search for solutions to today's energy supply challenges. It is overseen by a scientific committee comprised of highly experienced individuals in the areas of natural and applied sciences, business, and petroleum engineering.

About *Leading the Energy Transition* series

"Leading the energy transition" is a series of publicly available studies on low-carbon energy technologies conducted by the SBC Energy Institute that aim to provide a comprehensive overview of their development status through a technological and scientific prism.

About the Electricity Storage FactBook

This Factbook seeks to capture the current status of and future developments in electricity storage, detail the main technological hurdles and areas for Research and Development, and analyze the economics of a range of technologies.

Acknowledgements

In addition to internal reviews, this FactBook has been reviewed by Dr. Anthony Vassallo, who holds the Delta Electricity Chair in Sustainable Energy Development at the School of Chemical and Biomolecular Engineering of the University of Sydney.

For further information about SBC Energy Institute or to download the FactBook, please visit **www.sbc.slb.com/SBCInstitute** or contact us at **sbcenergyinstitute@slb.com**

Integrating intermittent sources of energy requires additional flexibility resources and results in a new momentum for electricity-storage solutions

Power systems are challenging to operate since supply and demand must be precisely balanced at all times. Power demand is a constant state of flux; although it generally follows predictable patterns, it is impossible to forecast with precision. As a result, power systems have always had to be flexible. At present, flexibility comes primarily from the generation side: system operators adjust the output of generators upwards or downwards in response to predefined time frames and ramping rates. By storing primary energy sources, such as coal and gas, or water in hydro dams, system operators have avoided the need to store electricity.

Wind and solar photovoltaic systems make demand-supply matching more difficult since they increase the need for flexibility within the system, but do not themselves contribute significantly to flexibility. The increased need for flexibility is reflected in the residual load variations (demand minus intermittent output). The minimal participation in flexibility pool resources is mirrored by the low capacity credit of wind and solar that are granted by system operators to measure the amount of power that they can reliably be expected to produce at peak of demand.

Flexibility management can be optimized by perfecting models for forecasting output from wind and solar plants, fine-tuning market regulations and refining the design of power systems. But additional flexibility will be needed in the form of demand-side participation, better connections between markets, greater flexibility in base-load power supply or electricity storage.

Electricity storage is a three-step process that consists of withdrawing electricity from the grid, storing it and returning it at a later stage. It consists of two dimensions: the power capacity of the charging and discharging phases, which defines the ability of the storage system to withdraw or inject electricity instantaneously from or into the grid; and the energy capacity of the storing phase, which measures how much energy can be stored and for how long. As a consequence, electricity storage has very different uses, depending on the combination of the power rating and discharge time of a device, its location within the grid and its response time.

The primary purpose of electricity storage consists of ensuring power quality and reliability of supply, whether it is to provide operating reserves, uninterrupted power-supply solutions to end-users, or initial power to restart the grid after a blackout. A secondary purpose of electricity storage is driven more by energy requirements. This involves leveling the load – storing power in times of excess supply and discharging it in times of deficit. Leveling enables the deferral of grid investment on a congestion node and optimal utilization of low-operating-cost power plants, and presents opportunities for price arbitrage. The increased penetration of variable renewables is making these applications more critical. It is also creating a new application, known as intermittent balancing, to firm their output or avoid curtailment. For these reasons, variable renewables have resulted in renewed interest in electricity storage.

The features of storage technologies must match application requirements

Unlike liquid or gaseous energy carriers, electrical energy is difficult to store and must usually be converted into another form of energy, incurring conversion losses. Nevertheless, many storage technologies have been developed in recent decades that rely on mechanical, electrochemical, thermal, electrical or chemical energy. Most of them are currently clustered in the investment “valley of death”, *i.e.* at the demonstration or early deployment phases, when capital requirements and risks are at their highest.

The applications electricity storage technologies are able to fulfill depend on their chemical and physical characteristics. Technologies must be assessed at the application level, taking into account power rating, storage duration, frequency of charge and discharge, efficiency and response time, and site constraints that determine power and energy density requirements.

In general, pumped hydro storage (PHS) and compressed air energy storage (CAES) are the most suitable for bulk storage applications. PHS uses the gravitational potential energy of two vertical reservoirs; water is pumped from a lower reservoir up to a higher reservoir during periods of off-peak demand, and the flow is reversed to drive a turbine during peak periods. CAES works by using electricity to compress air into a cavern or pressurized tank and later releasing the air to drive a turbine, which converts the energy back into electricity. However, both technologies face site availability issues.

Batteries are a major component of the storage landscape and can serve a wide range of applications with intermediate power and energy requirements. They differ according to their electrodes and electrolyte chemistries: sodium-sulfur (NaS) and lithium-ion (Li-ion) are the most suited for stationary storage thanks to their higher power and energy densities, and greater durability. Nevertheless, durability remains, together with costs and safety concerns, one of the biggest hurdles to commercial development. In addition to conventional batteries, research is being conducted into flow batteries, such as vanadium redox (VRB) or zinc-bromine (Zn/Br) batteries, which use the same reaction but with two separately stored electrolytes, allowing for power and energy decoupling. They are, for now, more costly due to their complex balance of system, and further development and demonstration efforts will be needed.

For applications where providing power in short bursts is the priority, flywheel, superconducting magnetic energy storage (SMES) and supercapacitors appear to be the most attractive, as a result of their high power density, high efficiency, high response time and long lifespan. However, costs are high and these technologies are currently at the demonstration phase.

Finally, despite its poor overall efficiency and high up-front capital costs, chemical storage seems to be the only way to provide the very large-scale and long-term storage requirements that could result from a power mix generated primarily by variable renewables.

Chemical storage consists of converting electricity into hydrogen by means of water electrolysis. It actually goes far beyond electricity storage since hydrogen can also be converted into synthetic natural gas or used directly as a fuel in the transportation sector or as feedstock in the industry. In contrast to other technologies, chemical storage is mainly driven by excess, rather than a shortage, of renewable energy. Thermal storage is also worth considering, but is mainly being developed as a means of electricity storage in association with concentrating solar power.

With the exception of pumped hydro storage, the deployment of electricity storage is at an embryonic stage

Electricity storage is not a new concept. At the end of 2012, the installed power capacity of electricity storage plants amounted to more than 128 GW. However, its development has been restricted to one technology: pumped hydro storage. Development of pumped hydro storage started in the 1960s, and the technology accounts for 99% of global installed capacity and for 78% of future storage projects – with 8.2 GW under construction and 8.2 GW planned, mostly in the US (41%) and China (25%).

After a slow start, compressed air energy storage may take off in the next few years. The first plant, a 290 MW facility in Germany, was commissioned in 1978. The second, a 110 MW plant in the US, was not built until 1991. Two large plants, with capacities of 300 MW and 150 MW, are under construction in the US, and further projects are planned in Germany and South Korea. However, the outlook is uncertain, given that several other compressed air projects have been suspended in the US, including a 2,700 MW venture in Norton, Ohio.

At the same time, large batteries are also being developed, with installed capacity amounting to almost 750 MW. Driven by development in Japan, sodium-sulfur batteries became the dominant technology in the 2000s and account for nearly 60% of stationary batteries installed (441 MW out of a total of 747 MW). In recent years, lithium-ion batteries have become more popular and account for the majority of planned battery projects. Although at a very early phase of deployment, with few projects announced, flow batteries could be a game changer in the medium term; research is being carried out at an intense rate in China and Australia.

With the exception of thermal storage, developed in recent years in conjunction with concentrating solar power plants, all other electricity-storage technologies remain marginal in terms of installed capacity. Despite the recent commissioning of a 20 MW plant in the US, flywheels struggle to find a sustainable value proposition; electrical storage technologies, either supercapacitors or superconducting magnetic energy storage, remain at an early phase of demonstration. Finally, interest in chemical storage is high in Europe, with several large-scale demonstration projects in Germany, Denmark and the UK. However, the primary aim of these projects is usually not to inject electricity back to the grid, but to green the gas or provide alternative transportation fuels.

Overall, interest in electricity storage is increasing, as indicated by the development of roadmaps by the International Energy Agency, the US and the UK.

Research, Development & Demonstration is making inroads into solving technological obstacles

R,D&D priorities vary according to the technology. For pumped hydro storage, the primary objectives are addressing the constraint of site availability and minimizing environmental impact by using sea-based or underground reservoirs. As a significant proportion of pumped hydro capacity is ageing and not designed to help balance variable renewable, R,D&D is also being directed at upgrading existing plants and increasing their flexibility, using variable-speed turbines, for instance.

Several compressed air energy storage concepts, which should increase efficiency by reducing or avoiding gas use, are also in development. Adiabatic compressed air involves the storage of waste heat from the air-compression process and its use to heat up the air during expansion. The isothermal design, meanwhile, aims to maintain a constant temperature. Several large-scale demonstration projects are planned or under development; these include RWE's 90 MW adiabatic Adele plant in Germany or SustainX's 1 MW isothermal project in the US. As with pumped hydro storage, artificial reservoirs, especially pressurized tanks, are also being developed in response to the limited availability of natural storage formations.

Battery research is focused on new materials and chemical compositions that would increase lifespan, enhance energy density and mitigate safety and environmental issues. For instance, lower-cost materials for the negative electrode of the lithium-ion battery are being tested, as are organic solutions to replace the water-based electrolytes of flow batteries. Liquid-air and liquid-metal concepts that use oxygen from the air instead of storing an oxidizing agent internally are often considered potentially disruptive, but their commercial prospects remain uncertain.

Finally, R,D&D of hydrogen-based technologies is highly active. Efforts are focused on: improving the viability of water electrolysis (by reducing the capital costs of proton exchange membranes and increasing efficiency through the use of high-temperature concepts); assessing the suitability of blending hydrogen with gas; developing methods of using hydrogen to manufacture synthetic fuels; and continuing to investigate hydrogen storage in the form of metal hydrides and in underground formations.

Despite growth in activity, funding for electricity storage R,D&D is still lagging behind that of other low-carbon-enabling technologies, such as smart grids. Most of the funding is being channeled into compressed air energy storage. Hydrogen R,D&D is also benefiting indirectly from growing interest in hydrogen-fuelled transportation.

The business cases for electricity storage are very complex and rarely viable under current market conditions and existing regulatory frameworks

The economics of electricity storage are difficult to evaluate since they are influenced by a wide range of factors: the type of storage technology, the requirements of each application and the system in which the storage facility is located.

The initial investment in a storage facility comprises two principal components: a cost per unit of power ($/kW) and a cost per unit of energy capacity ($/kWh). The costs of power of a pumped hydro storage plant, for instance, comprise the cost of the pump/turbine ($/kW) and the cost of energy capacity, which depends on reservoir capacity and elevation differential ($/kWh).

These costs vary significantly according to the technology being deployed. Reflecting their attractiveness in power-driven applications, flywheels and supercapacitors are characterized by low capital costs for power (from $200 to $400 per kW) but prohibitively high investment in energy capacity (from $500 per kW in applications with low energy needs to $50,000 per kWh for high energy requirements). Conversely, compressed air energy storage has relatively high capital costs per unit of power (from $400 to $800 per kW), but is considerably cheaper per unit of energy (from $2 to $150 per kWh). The combination of power rating and energy capacity is therefore crucial in assessing the competitiveness of different technologies. Applications dictate another major component of storage economics: the frequency of charging and discharging cycles. Cycling affects the amortization of capital costs and annual replacement costs, which have significant impacts on battery economics.

Finally, the price of electricity is equivalent to fuel cost. Consequently, electricity-price distribution – depicted by the location-dependent price-duration curve – is a key factor in storage economics. Usually, storage operators try to take advantage of electricity price spreads (charging when the price is low and discharging when it is high), but this is not possible in all applications.

Overall, compressed air energy storage and pumped hydro storage are the most cost-effective technologies for large-scale electricity storage with frequent cycles. Flywheels and supercapacitors will be preferred for very short storage periods and frequent use. Batteries are likely to be the cheapest solutions when the number of cycles is low.

However, the economics of electricity storage remain shaky. The benefits of storage can be evaluated according to three methods, based on: the market (*e.g.* bidding to supply power to the control market); avoided costs (*e.g.* deferred investment); or the intrinsic value of storage, using the willingness-to-pay of the customer (*e.g.* provide power quality). Costs tend to outweigh the financial benefits, although price arbitrage and grid-investment deferral may make investments in storage profitable in some countries. Bundling several storage applications together seems a strong lever in helping electricity storage to become profitable. Removing regulatory barriers, such as making storage plants eligible to participate in ancillary services, rewarding fast response assets, or allowing network operators to own storage facilities, is also required to enable the monetization of storage.

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Environmental and social impacts vary according to the technology and might hinder development in some cases

As with the economics, the environmental impact of electricity storage is difficult to assess. It is necessary to consider direct and localized impacts, which vary according to the technology used, as well as the impact of the generation source, electricity displaced upon discharging and the increase in generation needed to balance storage energy losses. There is, for instance, no environmental sense in storing low-cost power from coal at night to displace electricity generated during the day from gas or hydro peak power plants.

In terms of individual technologies, pumped hydro storage faces the greatest environmental problems. Due to its low energy density – 1 cubic meter of water over a height of 100 meters gives 0.27 kWh of potential energy – requirements for land and water are high. Closed-cycle plants using two artificial reservoirs reduce water use, but increase the flooded area. Higher elevation differentials and new concepts using seawater and wastewater could mitigate the technology's environmental impact.

Compressed air energy storage uses very little land, but is the only technology that directly emits greenhouse gases. That said, emissions are very low (equivalent to roughly one third of those of conventional gas turbine) and have been reduced in newer plants where exhaust gas is used to heat up the air. Moreover, emissions will be avoided in adiabatic and isothermal plants. Compressed air energy storage also has high water requirements for the formation of underground salt caverns and for cooling during operation.

Meanwhile, there are concerns over the energy intensity of batteries. According to a recent Stanford University study, over their lifetime batteries store only two to ten times the energy needed to build and operate them. This compares with ratios higher than 200 for pumped hydro storage and compressed air energy storage. The relatively low ratio for batteries results from their cycling life and the materials of which they are made, underlining the need for continuing research to improve durability and investigate new materials. Important safety issues that could compromise public acceptance must be addressed in the case of batteries and hydrogen solutions.

Finally, better communication and education are needed to improve the understanding of electricity storage among energy professionals, policy makers, students and the general public.

1. Introduction to electricity storage **10**
- **1.1** The need for electricity storage 11
- **1.2** Main applications 14

2. Electricity storage technologies **20**
- **2.1** Technology landscape 21
- **2.2** Technology cards 26

3. Status & future developments **48**
- **3.1** History 49
- **3.2** Installed capacity 50
- **3.3** Project pipeline 51

4. Research, Development & Demonstration **60**
- **4.1** Priorities 61
- **4.2** Funding 70

5. Economics, financing and key players **72**
- **5.1** Costs 73
- **5.2** Revenues 80
- **5.3** Financing 84
- **5.4** Key players 85

6. Environmental & social impacts **86**

Appendix & bibliography **92**

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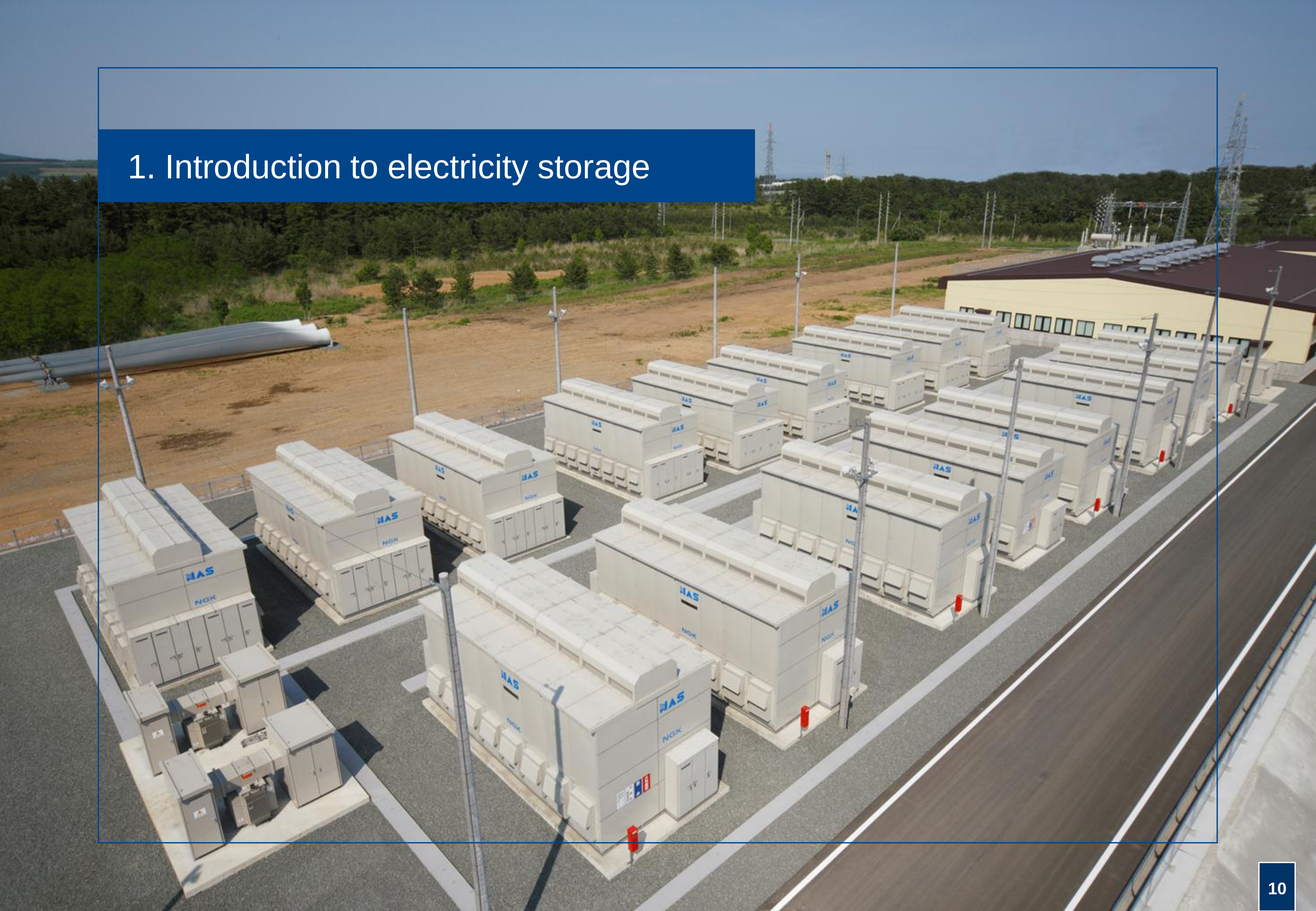
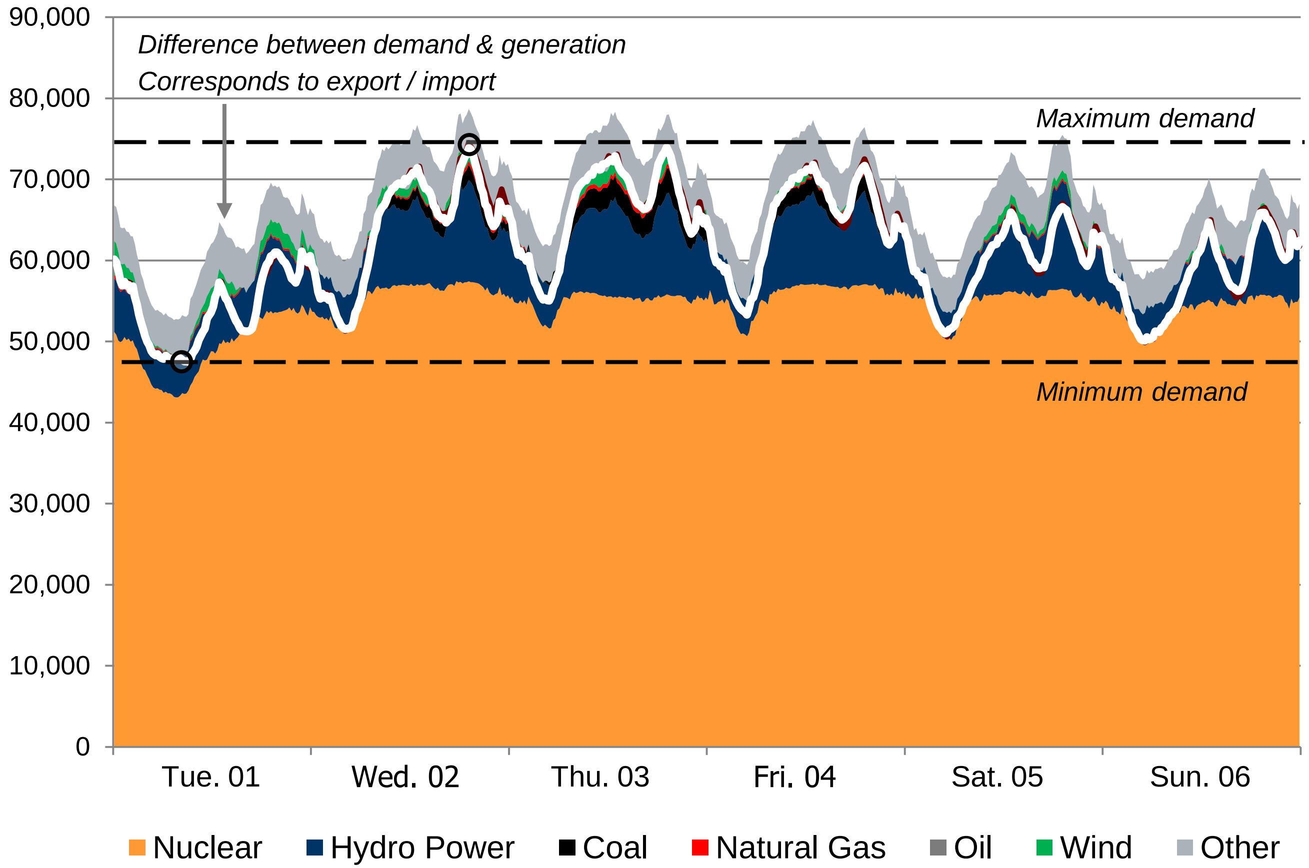
1. Introduction to electricity storage



Existing power systems avoid storing electricity by storing primary energy sources that supply flexible power plants

FRENCH WEEKLY LOAD AND SUPPLY CURVE AND SUPPLY BY TEHNOLOGY*
MW, January 2013



- **Electric power systems are challenging to operate**:
  - They require constant adaptability to demand in order to meet consumption needs and avoid costly blackouts;
  - Power consumption changes all the time. It has a daily, weekly, and seasonal pattern, but is impossible to predict with perfect accuracy.
- **Since demand is imperfectly predictable, in order to follow the load, generators are dispatched at the request of power grid operators;** they are chosen depending on the flexibility needed and on their marginal costs of production (merit order).
- **Electricity storage is therefore mostly avoided by storing primary energy resources** such as coal, gas, oil, uranium, biomass or water (hydropower), which can be converted to power at short notice.

Note: * The white curve represents demand. The other colors represent production by technology type. The difference between generation and demand is shown in grey and represents the difference between exports and imports.

Source: SBC Energy Institute Analysis based on Réseau de Transport d'Electricité website dataset (*www.rte-france.com/fr/developpement-durable/eco2mix*)

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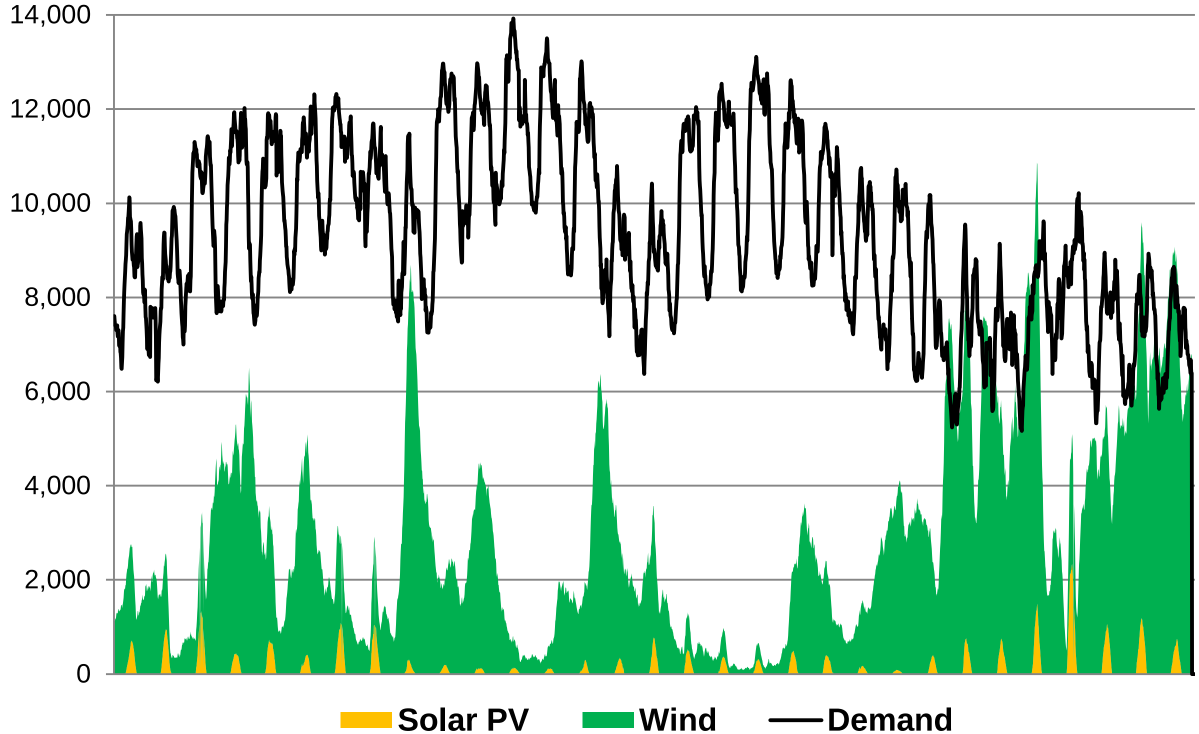
Wind and solar photovoltaic energies increase the need for flexibility without themselves contributing significantly to the flexibility of the power system

WIND & SOLAR PV GENERATION *VS.* DEMAND IN GERMANY
MW, December 2012 on a grid operating at 50 Hertz

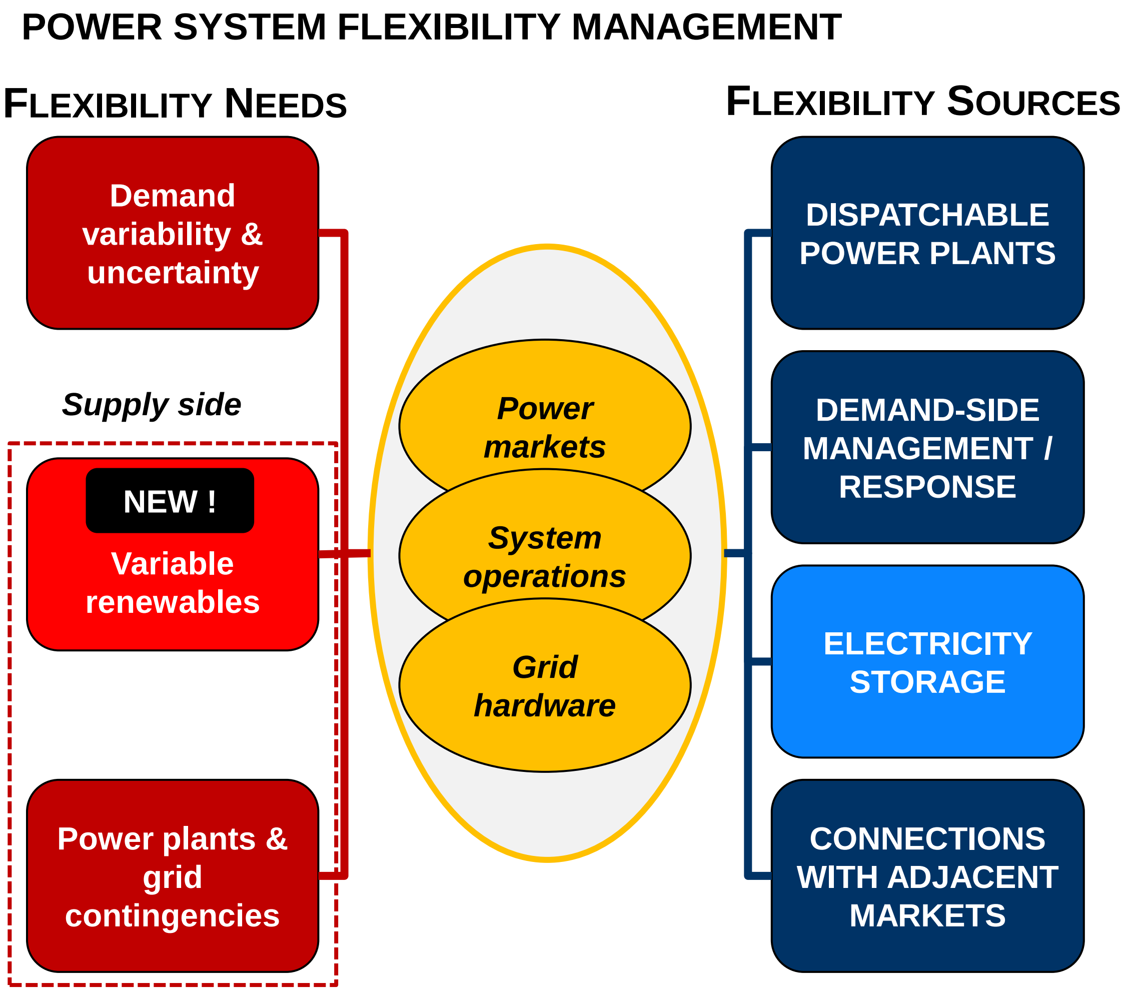


- **Wind and solar photovoltaic (PV) introduce variability and uncertainty on the supply side.** Their output varies according to daily or seasonal patterns and weather conditions, both of which are uncontrollable. Output is therefore:
  - ***Imperfectly predictable*** (notably harder to forecast than demand);
  - ***Imperfectly controllable****;*
  - ***Subject to steep ramp changes****.
- **The variable output of wind and solar increases the need for flexibility.** The residual load variations (demand minus intermittent output) on the graph illustrate the need the flexibility. In this example, the residual load variations fluctuate far more widely than the demand curve.
- **Wind and solar make a minimal contribution to the flexibility of the power system** because of uncertainty about their production reliability during peak demand, also known as the capacity credit. The International Energy Agency (IEA) estimates in its New Policies scenario that the capacity credits of wind and solar range between 5% and 20%**.

Note: * For instance, a wind farm producing at full load may have to shut down if turbine upper speed limit is reached.
** In actuality, this means in Europe that out of the 450 GW of installed capacity predicted by 2035 for Wind, only 22.5 GW will be available for the pool of flexibility resources to power operators. However, capacity credit varies by region and is typically higher where peak demand occurs during the sunniest hours (*e.g.* in the Middle East, where demand peaks are caused by the use of air-conditioning).

Source: SBC Energy Institute Analysis based on 50Hertz data archive (Wind and Solar Actual In Feed 2012, Control Load 2012)

Integrating variable renewables requires additional flexibility resources, resulting in the need for electricity storage



- **Up to a certain penetration rate*, the integration of wind and solar into the power mix can usually be managed using existing flexibility sources.** The threshold depends on the system's location and characteristics, and ranges roughly between 15% and 25%.
- **As the penetration of wind and solar within energy systems increases, interest in electricity storage will grow.**
  - Storage enables participants to profit from variations in the peak/off-peak ratio of the residual load arising from the combination of low demand and high variable generation or high demand and low generation. This has, for example, occasionally led to negative prices in some markets in recent years, creating opportunities for price arbitrage;
  - In systems that are highly dependent on variable renewables, electricity storage may be necessary in supplementing primary energy storage and ensuring security of supply. In the short to medium term, electricity storage is likely to be limited to island system or remote communities, replacing back-up diesel generators. It the longer run, it may also be needed in larger grids*.

Note: * Germany has modeled several power mixes for 2050, including one based entirely on renewables; in this case, residual load simulation projects indicate that the discrepancy between supply and demand is likely to range between a deficit of 84.7 TWh and a surplus of 82.7 TWh. As a result, long-term storage is likely to be needed to store electricity during periods of surplus supply and to release it into the grid when there is a shortage.

Source: IEA (2011), "Harnessing Variable Renewables"

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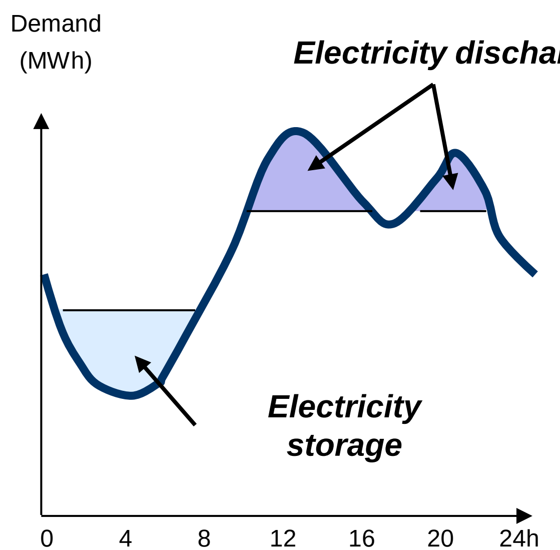
Electricity storage has two primary functions: leveling the demand curve and ensuring power quality and reliability by providing ancillary services

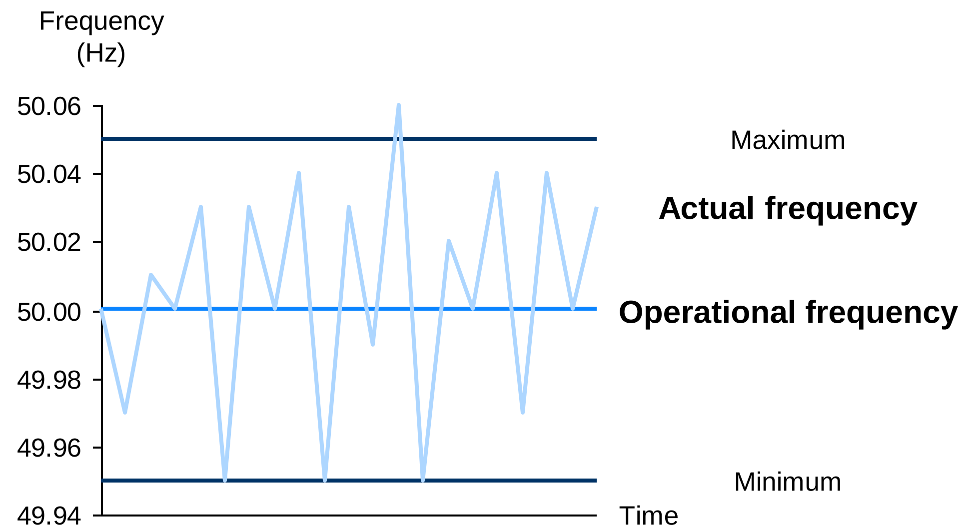
PRIMARY FUNCTIONS FOR ELECTRICITY STORAGE - ILLUSTRATIVE

LOAD LEVELING



Electricity storage is used to level the load over various timescales. Typically, electricity is stored during periods of low demand and discharged during periods of peak demand to reduce the peak/off peak amplitude (daily, weekly and seasonal demand). This can also occur over shorter timescales (hourly) to smooth the load and avoid activating peak plants.

ANCILLARY SERVICES



The system's frequency and voltage need to be maintained within technical limits to avoid instability and blackouts. This could be achieved by using fast-response electricity storage to inject or withdraw power as an alternative to conventional reserves(frequency response, spinning and non spinning, and replacement reserves).

Source: SBC Energy Institute Analysis based on IRES Proceedings 2012

Electricity storage has several operational applications

OPERATIONAL APPLICATIONS: MAIN GROUPS

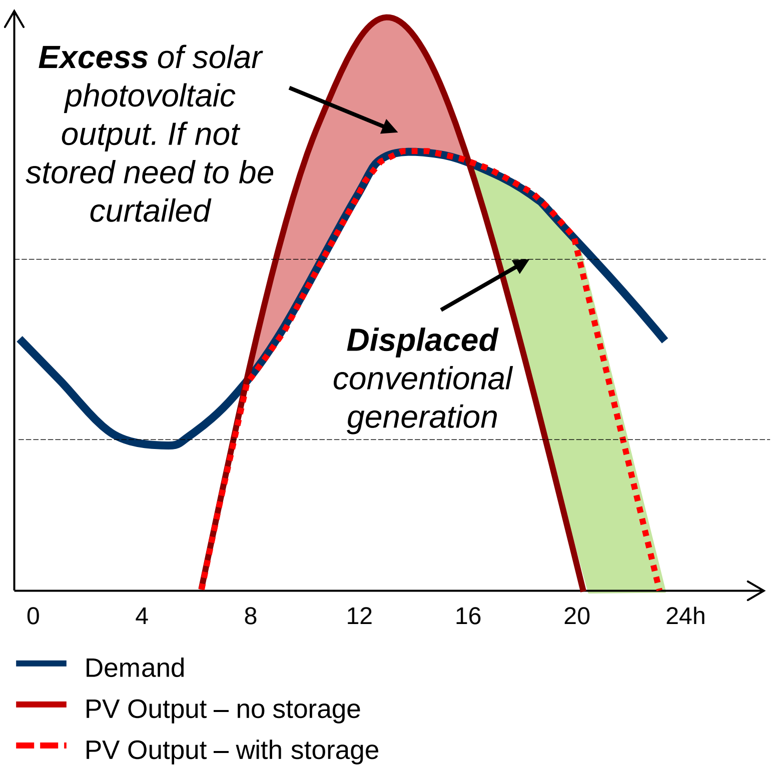
STORAGE	Application	Description
LOAD LEVELING	Power fleet optimization*	Maximize the share of base-load power plants with the lowest operational costs and minimize the need for flexible peak power plants and for shut-down and start-up. Charge when the price is low and discharge when the price is high (price arbitrage).
LOAD LEVELING	T&D** deferral	Avoid or defer an investment in grid infrastructure by avoiding peaks that may result in grid congestion or by building storage capacity close to demand bottlenecks. This will also reduce the congestion fees incurred when a line is congested.
LOAD LEVELING / ANCILLARY SERVICES***	Isolated area supply	Supply remote locations not connected to the grid (substitute or complement diesel generators in conjunction with renewable energy sources).
ANCILLARY SERVICES***	Provide operating reserve	Immediate or automatic mechanism that increases or decreases output to maintain frequency and voltage continuously within electricity network standards (frequency response, spinning or non-spinning or replacement reserves, depending on timeframe).
ANCILLARY SERVICES***	Ensure power quality	Replace devices that ensure power quality (*e.g.* voltage regulators, flexible AC transmission systems, Static VAR compensators) or ensure uninterrupted power supply without the need for back-up generators.
ANCILLARY SERVICES***	Black start services	Provide initial power supply to restart a power or gas grid after a full blackout. A requirement in all systems, this task is usually performed by diesel generator.

Note: * Power fleet optimization includes conventional and intermittent balancing (generator side) as well as peak shaving (customer side).
** T&D for transmission & distribution.
*** Ancillary services are usually monetized on the market or through bilateral agreements with the System Operator for provided services.

Source: SBC Energy Institute Analysis

Variable renewables make current applications more crucial and create their own need for storage to balance their intermittency

ILLUSTRATIVE MAXIMIZATION OF THE DAILY OUTPUT OF A SOLAR PHOTOVOLTAIC PLANT WITH ELECTRICITY STORAGE



- **Wind and solar are making the existing applications of electricity storage more important:**
  - ***Power quality and reliability*** is more at risk due to the variable and non-controllable output of wind and solar (*e.g.* sudden drops in voltage due to ramp events);
  - ***Load leveling*** may become essential as wind & solar increase the need for flexibility without themselves contributing significantly to the flexibility of the power system. Variable renewables are likely to increase the price spread between peak and off-peak periods, resulting in price arbitrage opportunities. As they come first in the merit order*, they may displace some of the capacity of baseload power plants and reduce the utilization rate of peak power plants, increasing the complexity of managing and optimizing the power fleet.

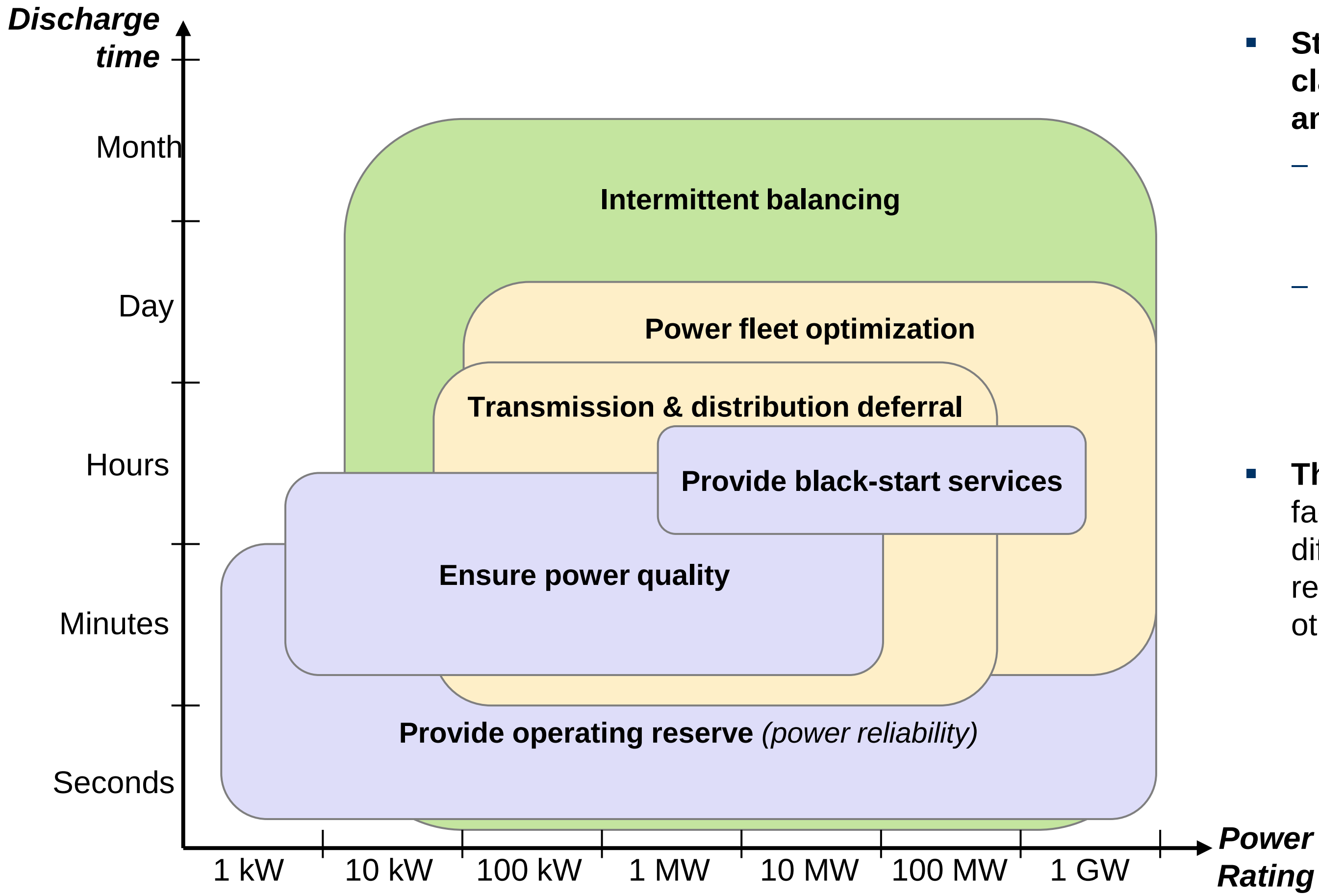
- **Wind and solar are also creating their own electricity storage applications:**
  - ***Firm & smooth output***: increase the reliability of wind and solar farms and attempt to correlate their output with demand to reduce flexibility needs and/or participate in flexibility sources;
  - ***Integrate distributed generation***: small scale PV panels can be connected to the distribution grid and create operational challenges (*e.g.* backflow over the limit);
  - ***Avoid curtailment***: for high penetration rates, the combination of low demand and high production can result in an excess of energy. Storage can avoid curtailment and, as a result, energy wastage.

Source: SBC Energy Institute Analysis

Application requirements depend largely on discharge time and power ratings, which determine cycling time and the importance of efficiency

APPLICATIONS DEPENDING ON POWER RATING & DISCHARGE TIME

Logarithmic scale, power rating in watt

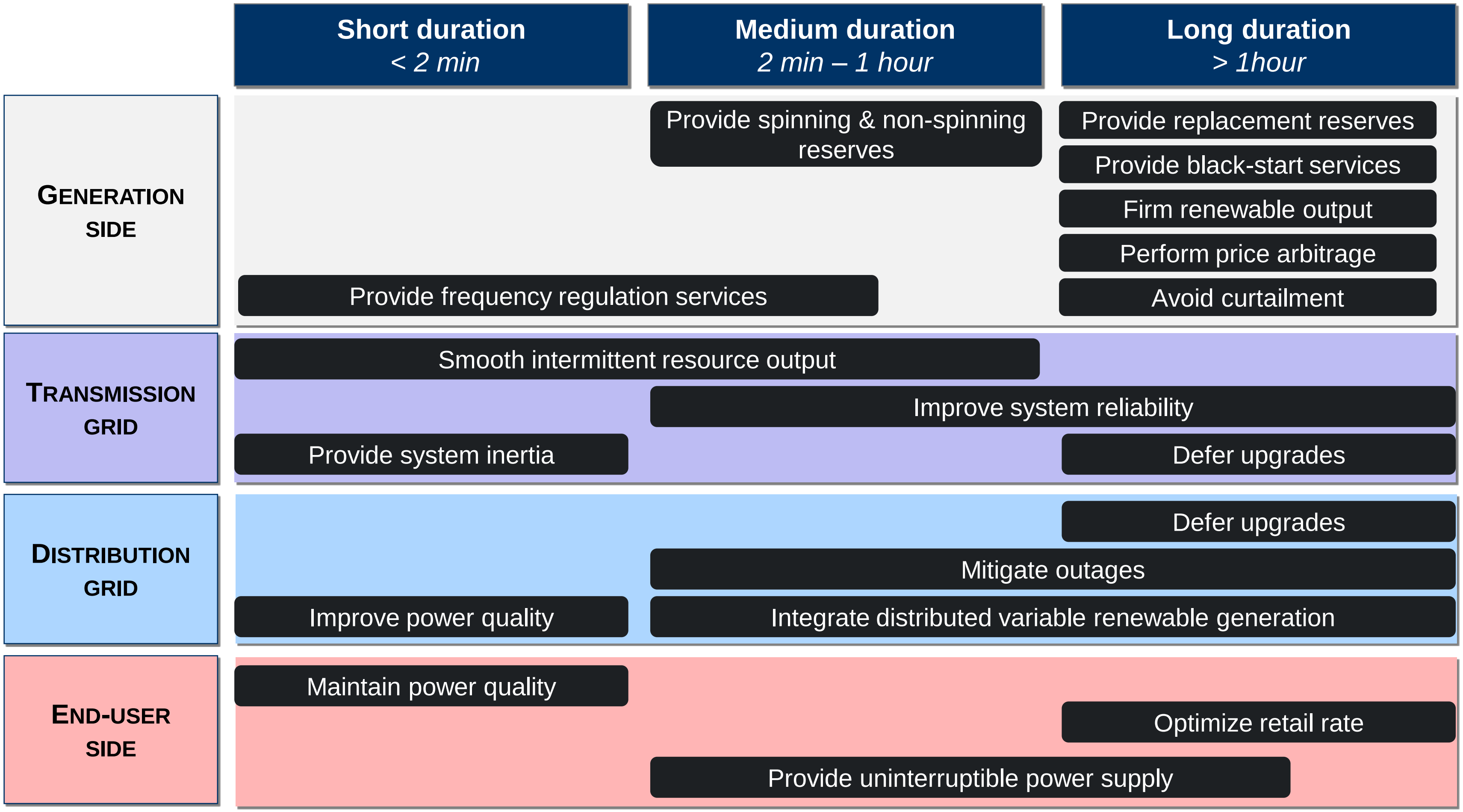


- **Storage applications are broadly classified according to their power rating and discharge time requirements:**
  - *Power rating* rates the storage device's instantaneous ability to withdraw/inject energy from/into the grid;
  - *The discharge time* indicates the time needed to provide this energy. It corresponds to the energy capacity of the storage divided by the power rating.
- **The power-to-energy ratio** is an essential factor in meeting the requirements of different applications. Some applications require long duration of output power, while others short injection of high power.

Source: SBC Energy Institute Analysis based on IEA ECES 2012

The type of storage application will have a significant impact on location of the facilities within the grid

APPLICATIONS DEPENDING ON OUTPUT DURATION & LOCATION ON THE GRID

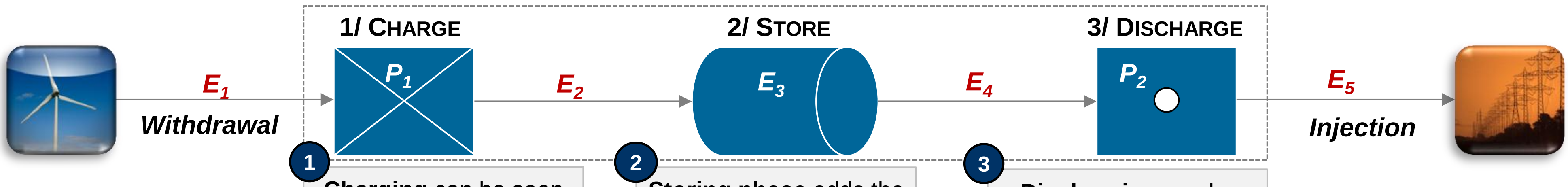


Note: For simplification, voltage & frequency regulation have been merged under power quality.

Source: SBC Energy Institute Analysis based on Southern California Edison (2010), “Moving Energy Storage from Concept to Reality”

All applications have specific technical requirements that will have to be matched with the characteristics of storage technologies

STORAGE SYSTEM PROPERTIES



1 — **Charging** can be seen as a form of consumption and is characterized by the rate at which energy can be withdrawn (power) and the time needed to start (ramping rate).

2 — **Storing phase** adds the time-shifting dimension and is characterized by the amount of energy the system can store (energy being equal to power multiplied by time).

3 — **Discharging** can be seen as a form of power generation and is characterized by the rate at which energy can be injected (power) and the time needed to start (ramping rate).

- **The properties of a storage system will determine the breadth of applications that it can serve: :**
  - The *power-to-energy* ratio determines the typical storage cycling time of the system and provides an indication of the cycling frequency (*e.g*. an 8 MW charging device with 48 MWh electricity storage capacity has a charging time of 6 hours. The same device will have a charging time of 30 minutes for an energy rating of 4 MWh, resulting in a higher cycling frequency);
  - The *round-trip efficiency* defines the efficiency of the system. It is measured by the energy injected compared with the energy withdrawn. The time-shifting ability can be limited by self-discharge losses (% of energy lost per day). The importance of having a highly efficient system increases with increasing cycling frequency (*e.g.* ancillary service *vs.* black start services).

- **The specific energy** (kWh/kg)**, energy density** (kWh/l) **and power density** (kW/l) **determine the land footprint**, which together with safety hazards and environmental impact could limit applicability of certain storage systems in certain locations by making licensing and permitting processes more difficult.

Source: SBC Energy Institute Analysis

2. Electricity storage technologies

Electricity storage is challenging and is usually achieved by means of conversion into other forms of energy

MAIN ELECTRICITY STORAGE TECHNOLOGIES GROUPED BY PHYSICAL OR CHEMICAL PRINCIPLES

1

MECHANICAL storage

- **Pumped hydro storage** (PHS)
- **Compressed air energy storage** (CAES) (& advanced concepts)
- **Flywheel** energy storage (FES)

2

THERMAL* storage

- **Hot-water** storage
- **Molten-salt** energy storage (MSES)
- **Phase change material** storage (PCM)

3

ELECTRICAL storage

- **Supercapacitors** (SC)
- **Superconducting magnetic energy storage** (SMES)

4

ELECTROCHEMICAL storage

- **Sodium-sulfur batteries** (NaS)
- **Lithium-ion batteries** (Li-ion)
- **Vanadium redox-flow batteries** (VRB)

5

CHEMICAL storage

- **Hydrogen**
- **Synthetic natural gas** (SNG)
- **Other chemical compounds** (Ammonia, Methanol…)**

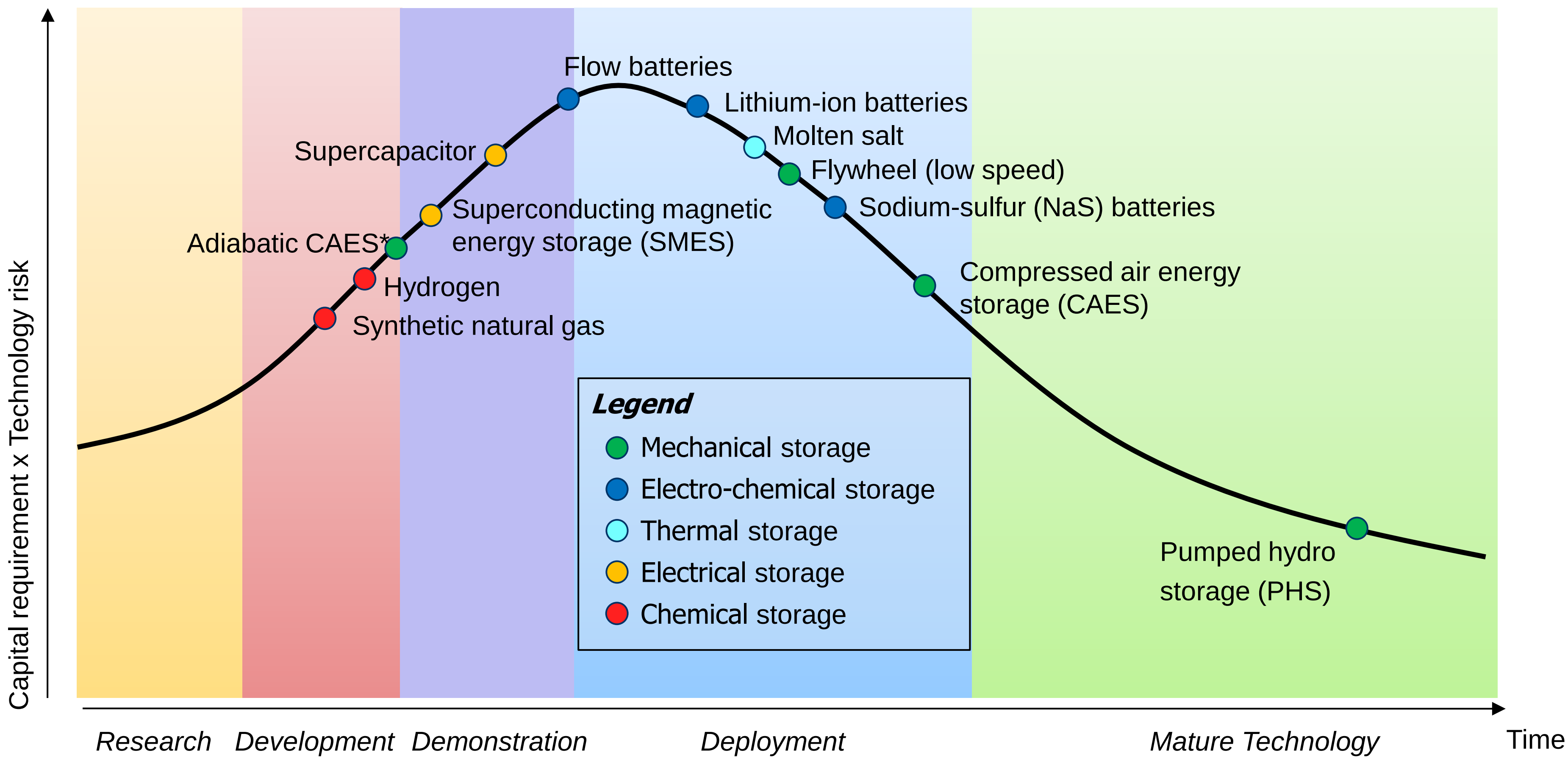
Note: * This FactBook only describes molten-salt thermal storage, which is the most developed thermal technology for electricity storage. Conventional thermal storage – which aims to supply heat and cooling without re-electrification – includes several other technologies (*e.g.* aquifer thermal energy storage and ice storage for cooling). Some may interact, support or complement electricity storage (*e.g.* combining solar-powered desalination plant and thermal storage, or leveraging individual water boilers as a means of electricity storage). For reasons of clarity, those interactions are not discussed in this FactBook, which sticks to pure electricity storage technologies.

** Subject to further processing, hydrogen can be stored as ammonia (NH_3), or methanol. These technologies are not covered in this FactBook.

Source: SBC Energy Institute Analysis

Electricity storage technologies are at very different levels of maturity with many clustered at the high capital requirement and risk stages

TECHNOLOGY MATURITY CURVE



Note: * CAES: compressed air energy storage.
Source: SBC Energy Institute Analysis

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Technologies are constrained by their underlying chemical or physical characteristics

MAIN TECHNICAL FEATURES OF STORAGE TECHNOLOGIES

	Power rating (MW)	Storage duration (h)	Cycling or lifetime	Self discharge [8]	Energy density (Wh/l)	Power density (W/l)	Efficiency	Response time
PHS[1]	100 - 1,000	4 - 12h	30 - 60 years	~0	0.2 - 2	0.1 - 0.2	70-85%	Sec - Min
CAES[2]	10 - 1,000	2 - 30h	20 - 40 years	~0	2 - 6	0.2 - 0.6	40-75%	Sec - Min
Flywheels	0.001 - 1	Sec - hours	20,000 - 100,000	1.3 -100 %	20 - 80	5,000	70-95%	< sec
NaS battery[3]	10 - 100	1 min - 8h	2,500 - 4,500	0.05 - 20%	150 - 300	120 - 160	70-90%	< sec
Li-ion battery[4]	0.1 - 20	1 min - 8h	1,000 - 10,000	0.1 - 0.3%	200 - 400	1,300 - 10,000	85-98%	< sec
Flow battery[5]	0.1 - 100	1 - 0h	12,000 - 14,000	0.2%	20 - 70	0.5 - 2	60-85%	< sec
Supercapacitor	0.01 - 1	Ms - min	10,000- 100,000	20 - 40%	10 - 20	40,000 - 120,000	80-98%	< sec
SMES[6]	0.1 - 1	Ms - sec	100,000	10 - 15%	~6	~2,600	80-95%	< sec
Molten salt	1 - 150	Hours	30 years	n/a	70 - 210	n/a	80-90%	Min
Hydrogen	0.01 - 1,000	Min - weeks	5 - 30 years	0 - 4%	600 (200 bar)	0.2 - 20	25-45%	Sec - Min
SNG[7]	50 - 1,000	hours-weeks	30 years	negligible	1,800 (200 bar)	0.2 - 2	25-50%	Sec - Min

Note: [1] PHS: pumped hydro storage; [2] CAES: compressed air energy storage; [3] NaS: sodium-sulfur; [4] Li-ion: lithium-ion; [5] Data for vanadium redox flow battery; [6] SMES: superconducting magnetic energy storage; [7] SNG: synthetic natural gas at ambient temperature; [8] Percentage of energy lost per day.

Source: Bradbury (2010), "Energy Storage Technology Review"; IEC (2011), "Electrical Energy Storage – White paper"

The underlying physical features of technologies determine their advantages and drawbacks

TECHNOLOGIES PROS & CONS

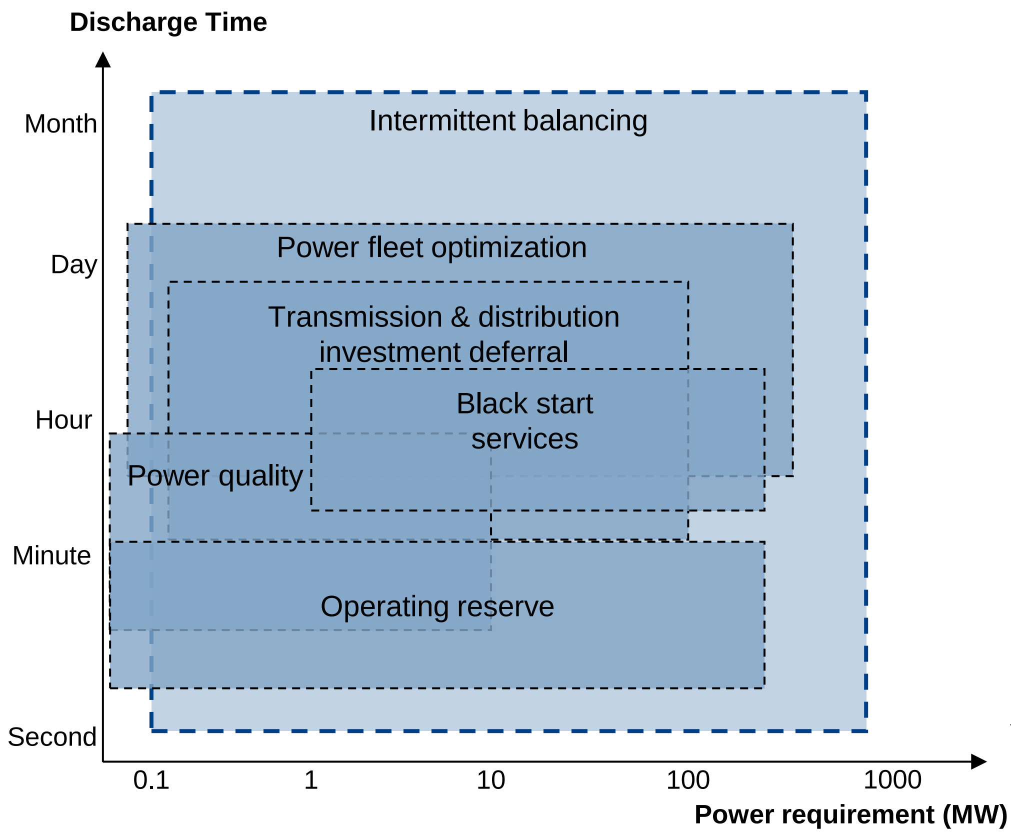
	Advantages	Drawbacks
PHS[1]	Commercial, large scale, efficient	Low energy density, availability of sites, depends on availability of water
CAES[2]	Cost, flexible sizing, large scale	Lack of suitable geology, low energy density, need to heat the air with gas
Flywheels	Power density, efficient, scalable	Cost, low energy density
NaS battery[3]	Efficient, density (power & energy), cycling (*vs.* other battery)	Safety, discharge rate (*vs.* other battery), must be kept hot
Li-ion battery[4]	Efficient, density (energy & power), mature for mobility	Cost, safety
Flow battery	Independent energy & power sizing, scalable	Cost (more complex balance of system)
Supercapacitor	High power density, efficient and responsive	Low energy density, cost ($/kWh), voltage changes
SMES[5]	High power density, efficient and responsive	Low energy density, cost ($/kWh), not widely demonstrated
Molten salt	Commercial, large scale	Niche for concentrating solar power plants
Hydrogen	High energy density, versatility of hydrogen carrier	Low round-trip efficiency, cost, safety
SNG[6]	High energy density, leverage current infrastructure	Low round-trip efficiency, cost

Note: [1] PHS: pumped hydro storage; [2] CAES: compression air energy storage; [3] NaS: sodium-sulfur; [4] Li-ion: lithium-ion; [5] SMES: superconducting magnetic energy storage; [6] SNG: synthetic natural gas.

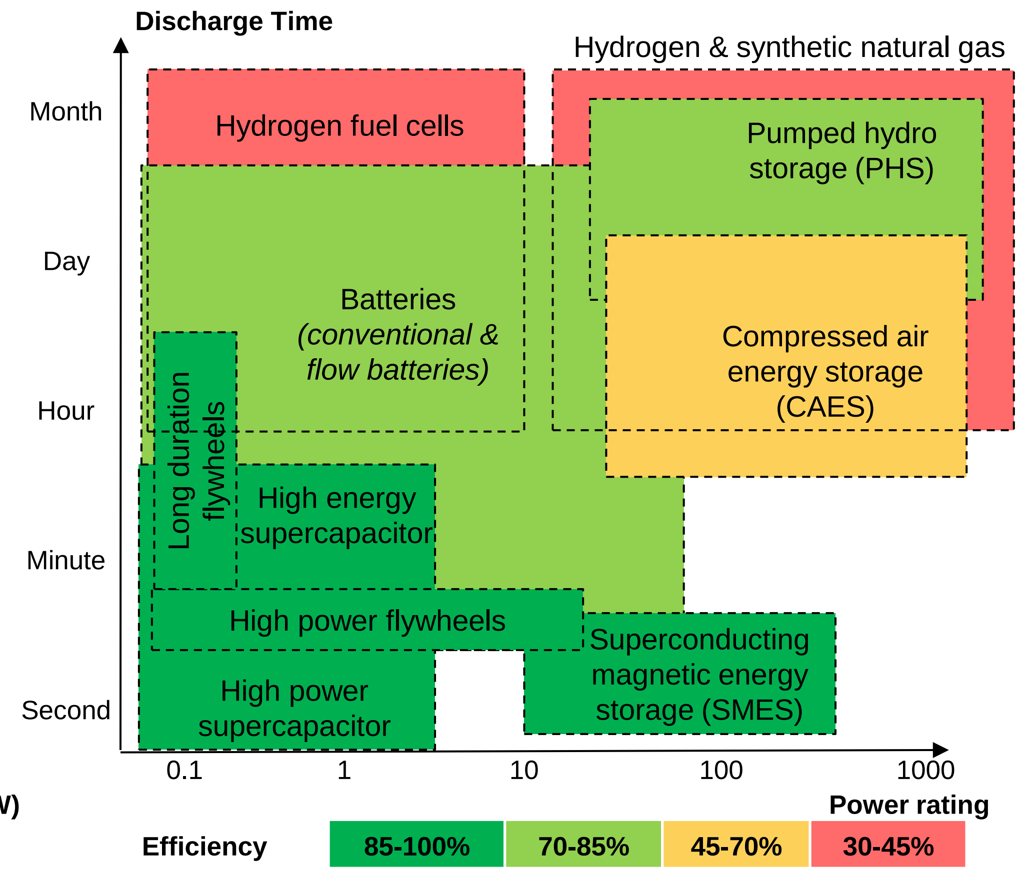
Source: SBC Energy Institute Analysis; IRENA (2012), "Electricity Storage – Technology Brief"

The features of storage technologies must be matched to the requirements of various applications

ELECTRICITY STORAGE APPLICATIONS
Discharge Time *vs.* Power requirements (MW)



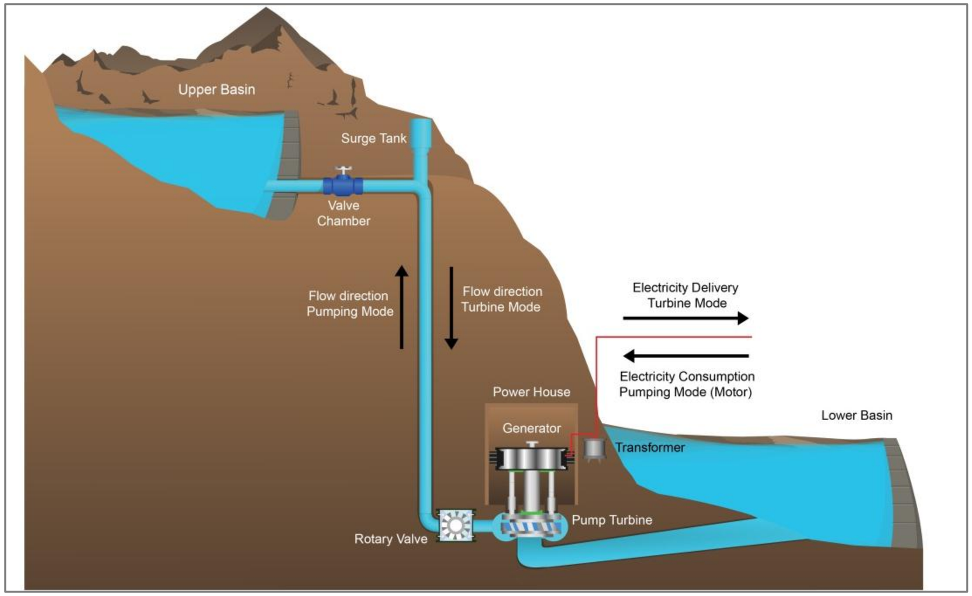
ELECTRICITY STORAGE TECHNOLOGIES
Discharge Time *vs.* Power capacity (MW)



Note: Supply to isolated areas has not been included as it is considered a mix of other applications. Technologies that contribute to black-start services only and serve for bridging before other plants kick in have been given a low score. Technologies that balance short-term fluctuations (sec-min) in renewable energy supply have been given a low score. Operating reserve does not appear on this figure as it encompasses a large range of timeframes, capacity and response-time requirements.

Source: SBC Energy Institute Analysis; EPRI (2010), "Electricity Energy Storage Technology Options", Bradbury (2010), "Energy Storage Technology Review"

Pumped hydro storage uses the gravitational potential energy of water by pumping / releasing water between two vertically separated reservoirs



PROS	CONS
− Cheapest way to store large quantities of energy with high efficiency over a long time; − Mature technology.	− Lack of suitable sites ; − Not fitted for distributed generation ; − Relatively low energy density results in indirect environmental impact.

- Pumped hydro storage makes use of two vertically separated water reservoirs. It uses low cost electricity to pump water from the lower to the higher elevated reservoir using either a pump and turbine or a reversible pump turbine. During periods of high demand, it acts like a conventional hydro power plant, releasing water to drive turbines and thereby generating electricity.
- Efficiency typically ranges between 70% and 85%. Losses mainly occur in the pumping and turbine stages, both of which are around 92% efficient, and to a lesser extent in the transformers, motors, generators and shaft line.
- In general, pumped hydro storage plants can reach their full power load in a few minutes, with reaction time ranging in the seconds. In recent years, variable-speed pump-turbines have been developed with the ability to generate power synchronously with the grid frequency, but pumping asynchronously, providing faster power adjustment.
- PHS requires high elevation differences between reservoirs or very large reservoirs to increase its relatively low energy density (1 cubic meter water released from a height of 100 meters gives 0.27 kWh of potential energy). This reduces the number of naturally suitable sites and can result in a large environmental footprint. Alternative solutions are being investigated to avoid these issues (*e.g.* artificial reservoirs underground or in the sea)

Source: SBC Energy Institute Analysis; Alstom (2012), "Pumped Hydro Storage Plants"

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Pumped hydro storage (PHS): fact card

KEY DATA

Installed capacity:	**~127 GW**	High/fast (dark green)
Power rating:	**100 - 1,000 MW**	High/fast (dark green)
Discharge duration:	**4 - 12 hours**	Light green
Response time:	**Sec - min**	Orange
Efficiency:	**70 - 85%**	Light green
Lifetime:	**> 30 years**	High/fast (dark green)

High/fast → **Low/slow**

EXAMPLES IN USE

- **Bath County** in Virginia, (USA) with a power rating of 3,003 MW (6 turbines) and an a elevation difference of 385 meters between the two reservoirs.
- **Guandong** in China with a capacity of 2,400 MW (8 turbines) and an elevation difference of 353 meters.

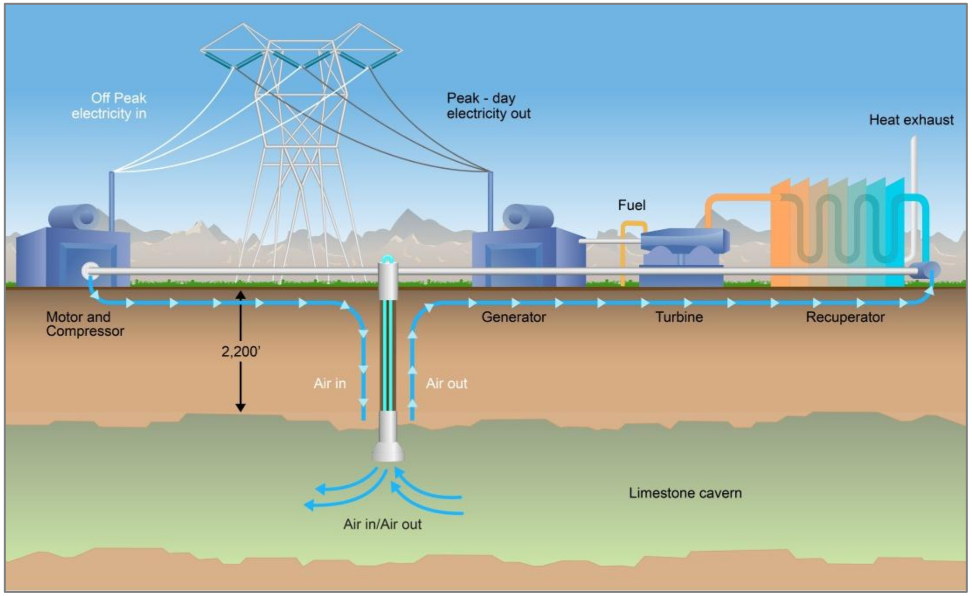
APPLICATIONS

Power fleet optimization	Stronger application (dark blue)
T&D deferral	Limited application (grey)
Power quality	Limited application (grey)
Black-start services	Light blue
Intermittent balancing	Light blue

Stronger application → **Limited application**

Source: SBC Energy Institute Analysis; Alstom (2012), "Pumped Hydro Storage Plants"; Bradbury (2010), "Energy Storage Technology Review"

Compressed air energy storage mechanically compresses air for storage and releases it during discharge to drive a turbine, producing electricity



PROS	CONS
− Large energy and power capacity; − Competitive, with low cost per kWh; − Adjustable to decentralized plants with artificial reservoirs.	− Constraints on availability of suitable geological formations; − Existing designs rely on gas burners.

- CAES uses electricity to compress air into a confined space (underground mines, salt caverns or underground aquifers), where it is stored. When needed, the pressurized air is released to drive the compressor of a natural gas turbine, thereby creating electricity.
- Much of the heat created during the compression phase is dissipated by intercoolers to comply with the technical requirements of the storage cavity. Therefore, a way must be found to re-heat the air prior to expansion in the turbine. Conventional diabatic systems use a natural gas burner to heat the air upon expansion. Gas consumption can be reduced by recycling flue gas from power plants for air preheating. This solution decreases system efficiency but is the simplest and the only one practiced today. Alternatives are being investigated, notably adiabatic systems that retain and store the heat emitted during compression and reintroduce it to the air upon expansion.
- In conventional designs, the cycle is achieved with electrically powered turbo compressors and turbo expanders with an efficiency of 45% to 55%, compared with more than 70% expected for adiabatic options. Ramp-up time is around 10 minutes and the system has a relatively long lifetime.
- Man-made salt caverns are the best option for storage but are not always geologically available. Alternative storage vessels are being investigated. Artificial pressure tanks have the advantage of being compatible with distributed applications. Using depleted gas fields is also worth considering, but the risk of the air reacting or mixing with residues of other gases must first be resolved.

Source: SBC Energy Institute Analysis; RWHT Aachen (2011), "Review of Energy Storage Options"

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Compressed air energy storage (CAES): fact card

KEY DATA

Installed capacity:	**400 MW**	light green
Power rating:	**10 - 1,000 MW**	dark green
Discharge duration:	**2 - 30 hours**	light green
Response time:	**Sec - min**	orange
Efficiency:	**40 - 75%**	orange
Lifetime:	**20 - 30 years**	dark green

High/fast → **Low/slow**

EXAMPLES IN USE

Two large-scale commercial plants:

- Huntorf, Germany (above): power output of 290 MW, two caverns of 150,000 m^3 for production over 4 hours. The power rating of the charging rate is 60 MW (*i.e.* it takes 12 hours to charge).
- McIntosh, Alabama (US): power output of 110 MW, discharge time of 26 hours. Air is stored in mined cavern of 283,000 m^3.

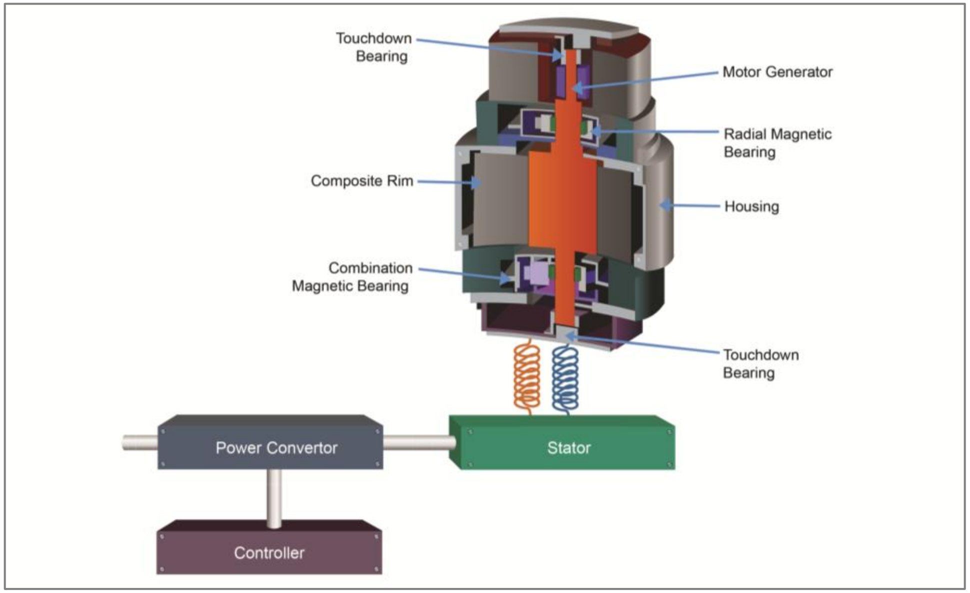
APPLICATIONS

- *Power fleet optimization*
- *T&D deferral*
- *Power quality*
- *Black-start services*
- *Intermittent balancing*

Stronger application → **Limited application**

Source: SBC Energy Institute Analysis; E.ON (2012), "Compressed Air Energy Storage – one promising technology in the future energy storage business"

Flywheels store electrical energy in the form of rotational energy via a flywheel rotating in a frictionless container



PROS	CONS
– High power density; – Low detrimental environmental impact; – High cycle life; – Independent power & energy sizing.	– Low energy density; – Difficult / expensive replacement of bearings; – High energy failures must be contained.

- Flywheels rely on the inertia of a mass rotating within a frictionless container. When charging, electricity is used to accelerate a rotor, called a flywheel, to very high speeds (30,000 to 50,000 rotations per minute). Energy can be stored for a long time as only small losses are incurred through friction with the container. To reduce these losses further, the rotor is levitated with permanent magnets and an electromagnetic bearing. When energy needs to be extracted from the system, the inertial energy of the rotor is used to drive a generator, reducing the flywheel's rotational speed.
- The flywheel system is usually contained within a single cabinet made of a benign and inert material, with low environmental impact and safety risks. The main components of the system include a power convertor, a stator, bearings and a rotor. Auxiliary components are the fuse boxes, contactors and cooling fans. The system requires limited maintenance and has a longer lifespan than batteries (up to 20,000 cycles). However, the replacement of bearings is expected to be difficult and expensive.
- The larger the rotational diameter and rotational speed of the flywheel, the higher its energy rating. The centrifugal forces induce fatigue, so fatigue-resistant materials such as special alloys or reinforced plastics are used. Flywheels tend to be high-power, low-energy devices. However, high-energy flywheels are being designed (several kW distributed over hours), and high-power flywheels (1 MW over 10 to 15 seconds) are already commercial.

Source: SBC Energy Institute Analysis; Sandia (2010), "Energy Storage for the Electricity Grid: Benefits & Market Potential Assessment Guide"

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Flywheel energy storage: fact card

KEY DATA

Installed capacity:	**45 MW**	Orange
Power rating:	**1 - 1,000 kW**	Red
Discharge duration:	**sec - hour**	Orange
Response time:	**10 - 20 ms**	Dark green
Efficiency:	**70 - 95%**	Dark green
Lifetime:	**15 - 20 years**	Light green

High/fast → **Low/slow**

EXAMPLES IN USE

- Stephentown, New York US (above): 20 MW plant with 200 flywheels providing frequency regulation with 4 second response time, storing 5 MWh over 15 minutes with a 85% round-trip efficiency.
- Okinawa (Japan): 23 MW plant from Toshiba, regulating frequency since 1996.

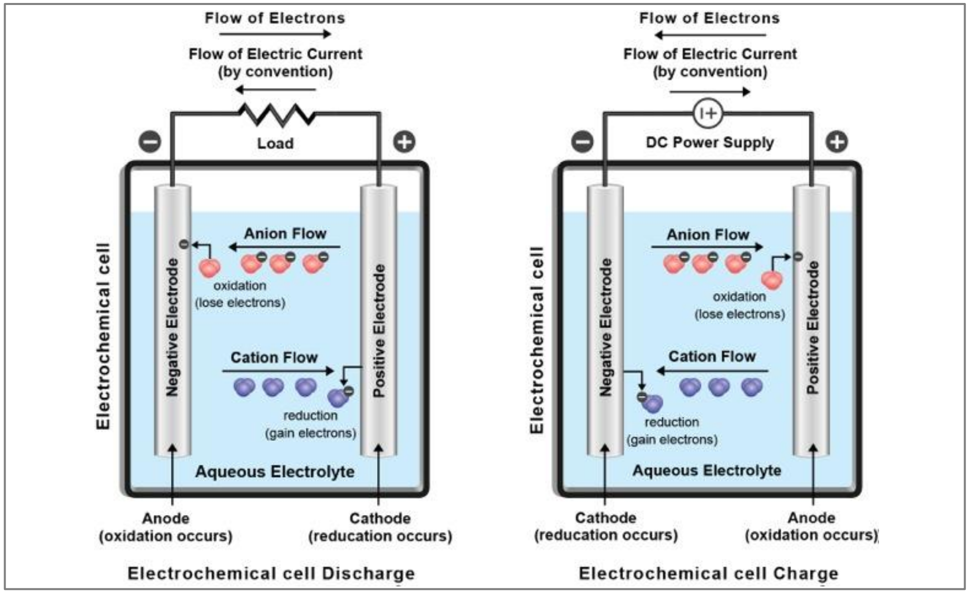
APPLICATIONS

Power fleet optimization	White
T&D deferral	White
Power quality	Dark blue
Black-start services	Medium blue
Intermittent balancing	Light blue

Stronger application → **Limited application**

Source: SBC Energy Institute Analysis; Bradbury (2010), "Energy Storage Technology Review"; IRENA (2012), "Electricity Storage – Technology Brief"

Batteries, categorized according to their chemical composition, are based on electro-chemical reactions where electrons flow between two electrodes



PROS	CONS
− High efficiency; − Extensive experience for portable applications; − Suitable for small to medium scale applications.	− Limited lifecycle; − Environmental & safety hazards; − Limited flexibility in power/energy sizing.

- Rechargeable batteries commonly used in mobile and portable applications are based on reversible electro-chemical reactions: during discharge, the negative electrode is oxidized, producing electrons, while the positive electrode is reduced, consuming electrons. These electrons flow through an external circuit, creating an electrical current (and vice versa upon discharging), while ions (anions and cations) flow through an electrolyte. The reaction requires active components (*i.e.* ions, contained in the electrode material and electrolyte solution) that will combine with electrons during reactions.
- The amount of energy than can be stored in a battery depends on the quantity of active components that can be stored in the electrolyte. The power rating is determined by the surface area of the electrodes and the resistance of the cell. However, this assumes there is enough electrolyte for the oxidation-reaction to be possible, meaning that power and energy sizing is usually closely related.
- Batteries are generally highly efficient (60-95%) and relatively responsive. Their performance is highly dependent on their chemistry (*i.e.* the chemical composition of their electrodes and electrolyte). They are suited both to small and large scale applications, as they can be used on their own, in series and in parallel. They face lifecycle limitations, present environmental and safety hazards, and are currently costly.

Source: SBC Energy Institute Analysis; Antonucci (2012), “Battery Energy Storage technologies for power system”; US DoE (2011), “Energy Storage – Program Planning Document”

Sodium and lithium batteries could suit stationary applications thanks to their longer life cycles and higher power & energy densities

COMPARING TECHNICAL PERFORMANCE OF BATTERIES

	Sodium-sulfur (NaS)	Lithium-ion (Li-ion)	Nickel-cadmium (NiCd)	Lead-acid (LA)
Efficiency *%*	70 - 90	85 - 98	60 - 80	70 - 90
Self-discharge *% energy / day*	0.05 - 20	0.1 - 0.3	0.067 - 0.6	0.033 - 0.3
Cycle lifetime *cycles*	2,500 - 4,500	1,000 - 10,000	800 - 3,500	100 - 2,000
Expected lifetime *years*	5 - 15	5 - 15	5 - 20	3 - 20
Specific energy *Wh / kg*	150 - 240	75 - 200	50 - 75	30 - 50
Specific power *W / kg*	150 - 230	150 - 315	150 - 300	75 - 300
Energy density *Wh / Liter*	150 - 300	200 - 400	60 - 150	30 - 80
Other consideration *(environment & safety)*	Need to be maintained at temperatures of 300°C to 350°C, entailing safety issues and preventing suitability to small-scale applications	Lithium is highly reactive and flammable, and therefore requires recycling programs and safety measures	Cadmium is a toxic metal that needs to be recycled. NiCd also requires ventilation & air conditioning to maintain the temperature	Lead is toxic and sulfuric acid is highly corrosive, requiring recycling and neutralization. Air conditioning required to maintain stable temperature

Source: Antonucci (2012), "Battery Energy Storage technologies for power system"; Bradbury (2010), "Energy Storage Technology Review"

Sodium-sulfur batteries (NaS): fact card

KEY DATA

Installed capacity:	**441 MW**	
Power rating:	**MW scale**	
Discharge duration:	**1 min - 8 hours**	
Response time:	**10 - 20 ms**	
Efficiency:	**70 - 90%**	
Lifetime:	**10 - 15 years**	

High/fast → **Low/slow**

EXAMPLES IN USE

- Rokkasho-Futamata Wind farm (Japan) (above): 34 MW plant with 17 sets of 2 MW NGK batteries with 238 MWh total storage capacity, used for load leveling and spinning reserves.
- St André La Réunion (France): EDF 1 MW plant (with 7 hours storage).

APPLICATIONS

- *Power fleet optimization*
- *T&D deferral*
- *Power quality*
- *Black-start services*
- *Intermittent balancing*

Stronger application → **Limited application**

Source: SBC Energy Institute Analysis, RWHT Aachen (2011), “Review of Energy Storage Options”, Antonucci (2012), “Battery Energy Storage technologies for power system”

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Lithium-ion batteries (Li-ion): fact card

KEY DATA

Installed capacity:	**139 MW**	Orange
Power rating:	**W to MW**	Orange
Discharge duration:	**1 min - 8 hours**	Orange
Response time:	**10 - 20 ms**	Dark green
Efficiency:	**85 - 98%**	Light green
Lifetime:	**5 - 15 years**	Orange

High/fast (dark green, light green, orange, red) **Low/slow**

EXAMPLES IN USE

- Laurel Mountain West Virginia (US): 32 MW plant in the wind farm from AES equipped with A123 batteries. Largest of its kind, commissioned in 2011 with 15 minutes storage capacity.
- La Aldea de San Nicolas in Canaria Island (Spain): 1 MW unit from Endesa with 3 MWh storage capacity equipped with Saft batteries.

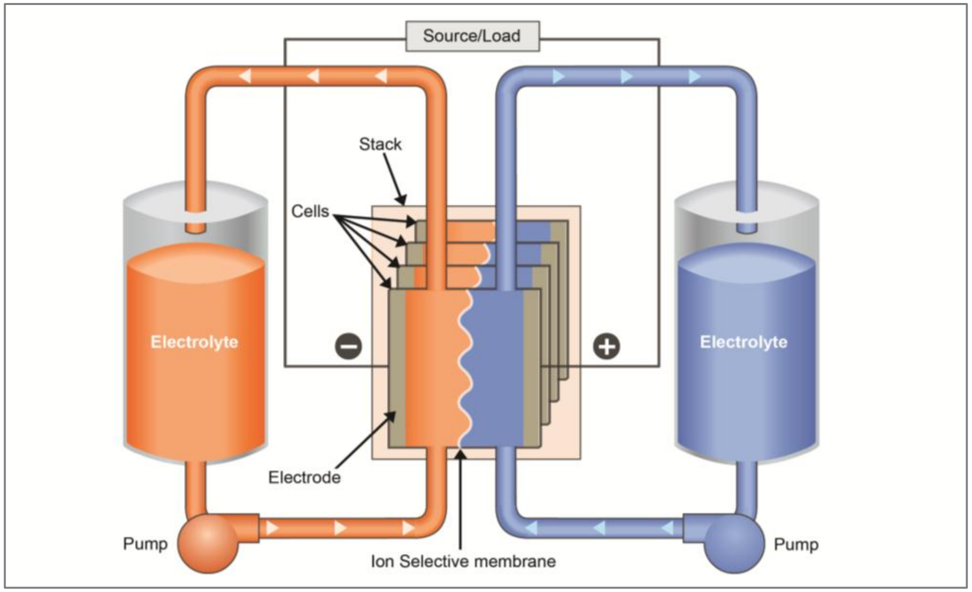
APPLICATIONS

Power fleet optimization
T&D deferral
Power quality
Black-start services
Intermittent balancing

Stronger application (dark blue, light blue, white) **Limited application**

Source: SBC Energy Institute Analysis, RWHT Aachen (2011), "Review of Energy Storage Options"; Antonucci (2012), "Battery Energy Storage technologies for power system"

Unlike conventional batteries, flow batteries rely on two separately stored electrolytes to decouple their power and energy capacities



PROS	CONS
− Independent energy & power sizing; − Scalable for large applications; − Longer lifetime in deep discharge.	− More complex than conventional batteries; − Early stage of development.

- The electrochemical process in flow batteries is comparable to that in conventional batteries. Ions contained in the electrolytes move from the negative and positive electrodes, upon charging and discharging, through a selective polymer membrane. A cooling system is usually needed, as charging and discharging releases heat.
- Unlike conventional batteries, flow batteries contain two electrolyte solutions in two separate tanks, circulated through two independent loops. The chemical composition of the electrolyte solution defines the sub-categories of batteries, the most important being Vanadium Redox (VRB) and Zinc-Bromine (Zn/Br).
- This more complex design allows the dissociation of power (defined by the number of cells in the stack and the size of electrodes) and energy (defined by the volume and concentration of the electrolytes).
- Operational temperature is usually between 20°C and 40°C,but higher temperatures are possible, provided plate coolers are used to avoid over-heating the plates. Flow batteries are usually between 65% and 80% efficient, allow approximately 10,000 to 20,000 cycles, and have a short response time.

Source: SBC Energy Institute Analysis, EPRI (2010), “Electricity Energy Storage Technology Options”

Vanadium redox flow (VRB) batteries: fact card

KEY DATA

Installed capacity:	**32 MW**	orange
Power rating:	**100 kW - 20 MW**	orange
Discharge duration:	**1 - 10 hours**	light green
Response time:	**10 - 20 ms**	dark green
Efficiency:	**60 - 85%**	light green
Lifetime:	**5 - 20 years**	orange

High/fast (dark green, light green, orange, red) **Low/slow**

EXAMPLES IN USE

- Tomamae, Hokkaido (Japan): 4 MW plant with 6 MWh of storage (90 minutes) composed of 16 modules of 250 kW each, located in a 30.6 MW wind farm.
- Kitangi (Kenya): hybrid power system at an off-grid site. 5 kW/30 kWh VRB system coupled with a diesel generator.

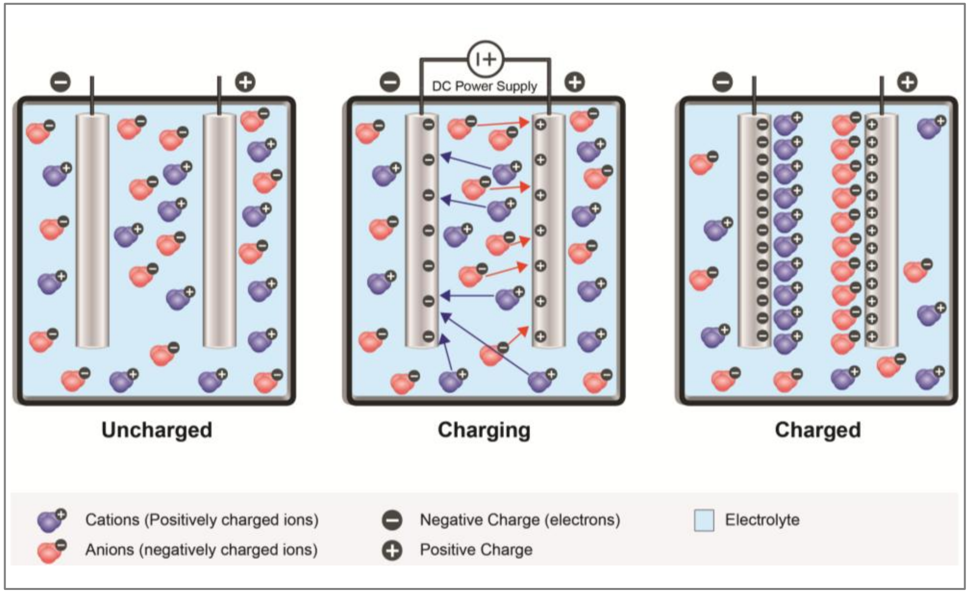
APPLICATIONS

Power fleet optimization	medium
T&D deferral	stronger
Power quality	light
Black-start services	stronger
Intermittent balancing	stronger

Stronger application (dark blue, light blue, white) **Limited application**

Source: SBC Energy Institute Analysis; Antonucci (2012), "Battery Energy Storage technologies for power system"

Supercapacitors polarize an electrolytic solution to store energy electrostatically



PROS	CONS
– High efficiency; – High cycle fatigue life; – Scalable / flexible; – High power.	– Low energy; – Requires power conditioning to deliver a steady output power; – Expensive per unit of energy capacity.

- Supercapacitors are also known as ultra capacitors or electrochemical double-layer capacitors. Conventional capacitors consist of two conducting carbon-based electrodes separated by an insulating dielectric material. When a voltage is applied to a capacitor, opposite charges accumulate on the surfaces of each electrode. The charges are kept separate by the dielectric, thus producing an electric field that allows the capacitor to store energy. Supercapacitors utilize an electrochemical double-layer of charge to store energy. As voltage is applied, charge accumulates on the electrode surfaces. Ions in the electrolyte solution diffuse across the separator into the pores of the electrode of opposite charge. However, the electrodes are engineered to prevent the recombination of the ions. Thus, a double-layer of charge is produced at each electrode.
- Capacitance, the ability of a body to store electrical charge, increases in proportion to the surface area of the electrodes and in inverse proportion to the distance between the electrodes. To maximize their capacitance (energy stored), supercapacitors use high-surface-area electrodes (up to 1,000 m^2/g) made of special materials such as activated carbon with distance of charge separation in the order of one ten-billionth of a meter.
- Supercapacitors are high-power, low-energy devices that can react very quickly. Due to the absence of a chemical reaction (unlike batteries), they can withstand a very high number of cycles (up to 100,000). They are highly efficient (from 80% to 95%), but, because the voltage varies linearly with the charge contained in the system, they require power electronics to ensure steady output.

Source: SBC Energy Institute Analysis; Bradbury (2010), “Energy Storage Technology Review”

Supercapacitors: fact card

KEY DATA

Installed capacity:	**N/A**	red
Power rating:	**kW - MW**	red
Discharge duration:	**ms - min**	orange
Response time:	**10 - 20 ms**	dark green
Efficiency:	**80 - 98%**	dark green
Lifetime:	**4 - 20 years**	light green

High/fast (dark green, light green, orange, red) **Low/slow**

EXAMPLES

- Palmdale California (US) (above): can provide 450 kW in 30 seconds to provide uninterruptible power supply to a water-treatment facility, with Maxwell Technologies capacitors.
- La Palma in the Canary Islands (Spain): Endesa's STORE project, one of few ventures with financing secured, will have a capacity of 4 MW and 6-second storage capacity.

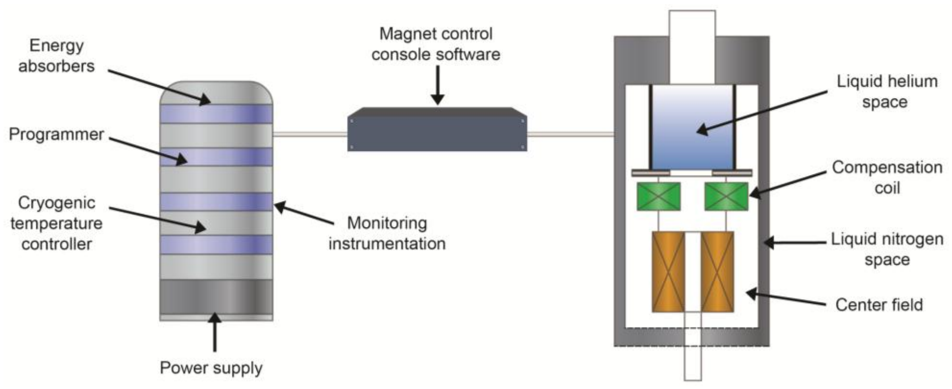
APPLICATIONS

Power fleet optimization	white
T&D deferral	white
Power quality	dark blue
Black-start services	light blue
Intermittent balancing	light blue

Stronger application (dark blue, light blue, white) **Limited application**

Source: SBC Energy Institute Analysis; Bradbury (2010), "Energy Storage Technology Review"

Superconducting magnets store electricity in a magnetic field

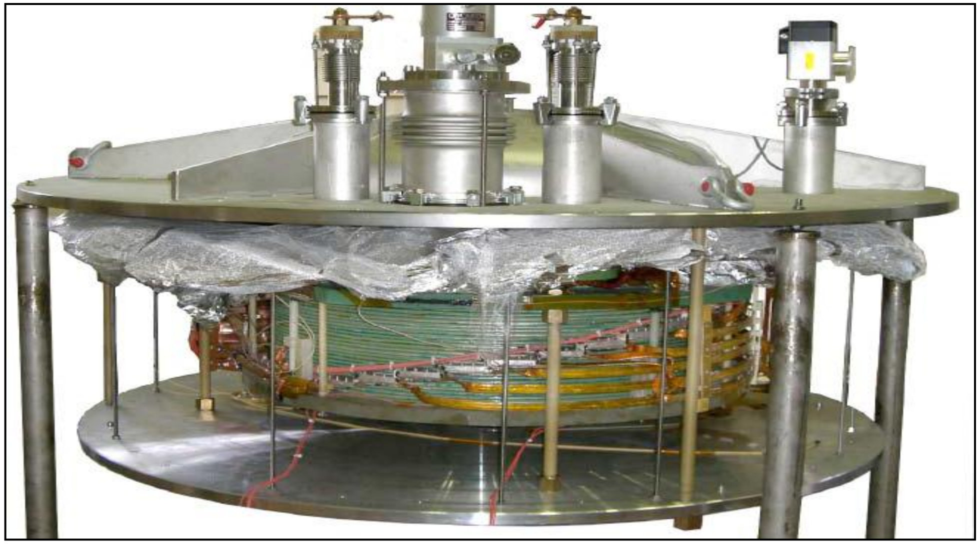


PROS	CONS
− High power density; − Quick response & charging time; − High efficiency; − Low maintenance.	− High cost of energy; − Complexity of the system; − Need to be kept at cryogenic temperatures.

- Superconducting magnetic energy storage devices (SMES) store electricity in a magnetic field generated by current flowing through a superconducting coil. The coil, made from a superconducting material, has no resistance when current is passed through it, reducing losses to almost zero. However, to maintain the superconducting state, a refrigeration system (*e.g.* using liquid nitrogen) is used.
- As well as the coil and the refrigeration system, SMES require power electronics such as Alternating Current/Direct Current (AC/DC) converters to control the flow of the current into and out of the coil that charges and discharges the SMES. They also need a physical structure to mechanically support the coil, which is subjected to magnetic forces during operations, providing protection and additional equipment for system control.
- SMES react almost instantaneously and have a very high cycling life. They require limited maintenance and can achieve high efficiencies, with only between 2% and 3% losses resulting from AC/DC converters. However, due refrigeration’s high energy requirements, the complexity of the system and the high cost of superconductors, SMES are currently at an early demonstration phase and is only suitable for short-term storage.

Source: SBC Energy Institute Analysis; CEA (2009), “Experience in manufacturing a large HTS magnet for a SMES”; EPRI (2010), “Electricity Energy Storage Technology Options”

Superconducting magnetic energy storage (SMES): fact card



KEY DATA

Installed capacity:	**N/A**	Low/slow
Power rating:	**MW**	High/fast (light green)
Discharge duration:	**ms - sec**	Low/slow
Response time:	**< 100 ms**	High/fast
Efficiency:	**80 - 95%**	High/fast
Lifetime:	**high**	High/fast

High/fast → **Low/slow**

EXAMPLES

– Anchorage Alaska (US): 500 kWh project using American Superconductor products for the municipal light & power plant.

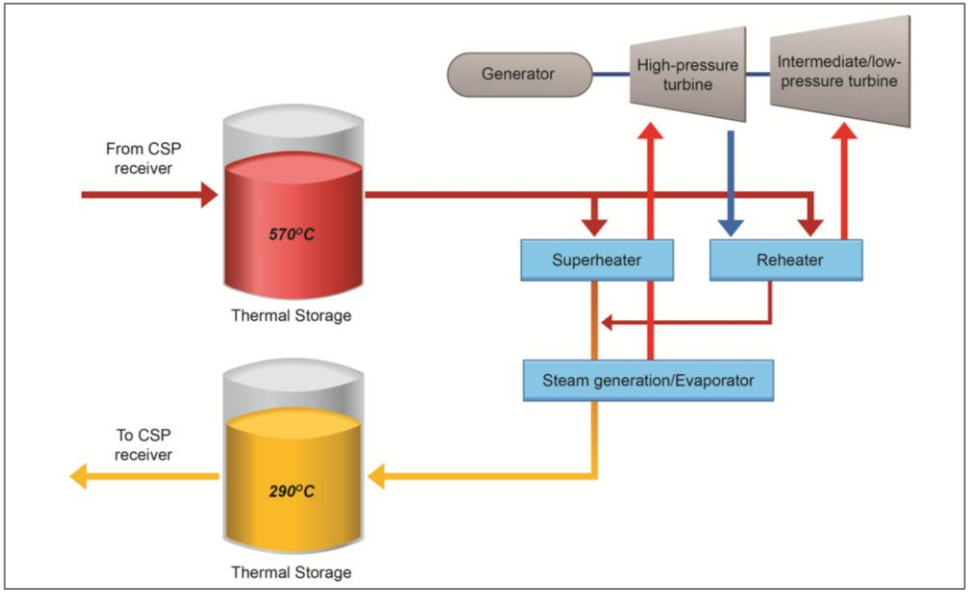
APPLICATIONS

Power fleet optimization	Limited application
T&D deferral	Limited application
Power quality	Stronger application
Black-start services	Medium application
Intermittent balancing	Medium application

Stronger application → **Limited application**

Source: SBC Energy Institute Analysis, EPRI (2010), "Electricity Energy Storage Technology Options"

Molten salts are an energy storage medium that stores heat from concentrating solar radiation



PROS	CONS
– Commercial; – Large scale; – Low cost.	– Niche for concentrating solar plant for power applications; – Molten salts can be corrosive; – Must not be allowed to freeze.

- Thermal storage has been investigated as a method of storing heat generated by the optical concentration of solar energy in concentrating solar power (CSP) plants*.
- Indirect storage systems require a heat exchanger to store heat in a separate circuit, usually oil-based. Direct storage systems include a storage tank directly linked to the primary circuit. Molten salts are used as a working fluid since they can serve both as a heat-transfer fluid and as heat-storage medium, making a heat exchanger unnecessary. Molten salts allow the use of higher temperatures, smaller storage tanks and higher steam-cycle efficiency. They have become the dominant technology.
- Molten salt is a mixture of 60% sodium nitrate and 40% potassium nitrate. It is non-flammable and non-toxic, with a low melting point, of 221°C. Salts are kept liquid at 290°C in an insulated cold tank, pumped through pipes, heated to 570°C by the CSP panels and sent to an insulated, hot storage tank. During discharge, hot salts are pumped through a superheater followed by a conventional steam generator, producing steam to drive a turbine. The salts are then returned to the cold tank and the process can begin again.
- Molten salt is already capable of storing large amounts of energy. It is capable of storing energy for up to 15 hours, and achieving high levels of efficiency. Despite being limited to CSP technology for power applications, it could play an important role in countries with high direct normal irradiance, such as the MENA region*.

Note: For more information about concentrating solar technologies : SBC Energy Institute FactBook, http://sbc.slb.com/SBCInstitute/Publications.aspx.
Source: SBC Energy Institute Analysis; IRENA (2012), "Electricity Storage – Technology Brief"

Molten salts energy storage (MSES): fact card

KEY DATA

Installed capacity:	**170 MW**	light green
Power rating:	**MW scale**	light green
Discharge duration:	**hours**	light green
Response time:	**min**	yellow
Efficiency:	**80 - 90%**	dark green
Lifetime:	**30 years**	light green

High/fast → **Low/slow**

EXAMPLES

- Aldiere, Grenada (Spain): Andasol 150 MW CSP parabolic plant include 7.5 hours of storage (3 series of two tanks containing 28,500 tons of Molten Salt).
- Tonopah Nevada (US): Crescent Dune 110 MW CSP tower plant include 10 hours storage capacity.

APPLICATIONS

Power fleet optimization

T&D deferral

Power quality

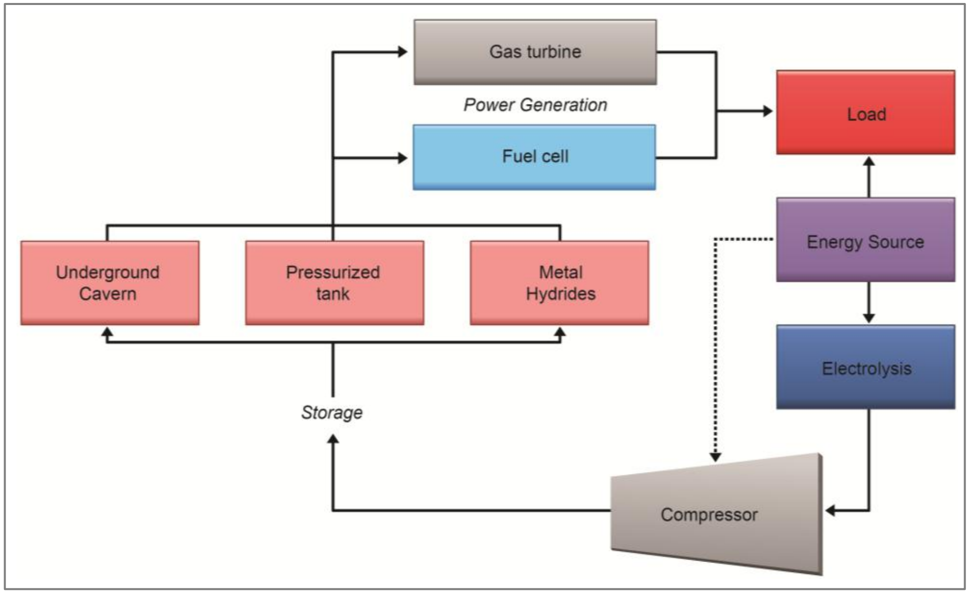
Black-start services

Intermittent balancing

Stronger application → **Limited application**

Source: SBC Energy Institute Analysis; IRENA (2012), "Electricity Storage – Technology Brief"

Hydrogen is the only technology to offer inter-seasonal storage, but it also suffers from low efficiencies, of 35-45%



PROS	**CONS**
– Scalable from distributed to large scale long term large scale storage; – Low detrimental effect on environment.	– Low round-trip efficiency; – High capital cost; – Safety concerns; – Low energy density at ambient conditions.

- Hydrogen energy storage technologies are based on the chemical conversion of electricity into hydrogen. Electrolysis is used to split water (H_2O) into its constituent elements, Hydrogen (H_2) and Oxygen (O_2). Due to its low atomic mass, it has an unrivalled specific energy. The electrolysis process can be reversed (*i.e.* hydrogen and oxygen generate electricity and water) to feed electricity back into the grid, using a fuel cell. Otherwise, hydrogen can be passed through heat engines in a similar way to natural gas, to produce electricity.
- Hydrogen can be stored in three main ways, each with different implications for the energy capacity of the system and its layout: as a gas in very large underground caverns within geological formations or in high-pressure tanks; as a liquid in cryogenic tanks; or as solid or liquid hydrides (*e.g.* ammonia, magnesium).
- Hydrogen storage technologies can capitalize on the experience of the chemical and petrochemical industries, which have long used hydrogen as a feedstock. These technologies have minimal environmental impacts and are highly reliable and responsive. However, some losses are unavoidable during the conversion and reconversion process and investments in conversion facilities are required.

Note: For more information about hydrogen technologies: SBC Energy Institute Study on hydrogen, http://sbc.slb.com/SBCInstitute/Publications.aspx.
Source: SBC Energy Institute Analysis; FuelCellToday (2013), "Water Electrolysis & Renewable Energy Systems"

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Hydrogen energy storage: fact card

KEY DATA

Installed capacity:	**~2 MW**	red
Power rating:	**kW - GW**	dark green
Discharge duration:	**Min - Weeks**	dark green
Response time:	**sec - min**	light green
Efficiency:	**25 - 45%**	yellow
Lifetime:	**5 - 30 years**	light green

High/fast → **Low/slow**

EXAMPLES

- Utsira project in Norway: excess of power from two 600 kW wind turbines is converted into hydrogen by a 48 kW electrolyzer and stored in compressed tanks (2,400 m^3 at 200 bar) and can supply a 55 kW hydrogen combustion engine.

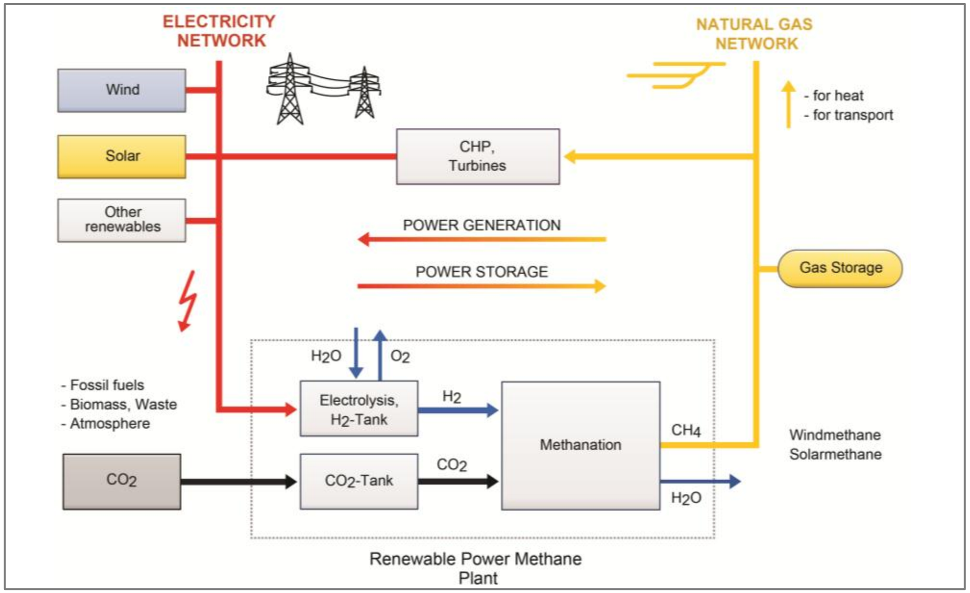
APPLICATIONS

Power fleet optimization
T&D deferral
Power quality
Black-start services
Intermittent balancing

Stronger application → **Limited application**

Source: SBC Energy Institute Analysis; FuelCellToday (2013), "Water Electrolysis & Renewable Energy Systems"

Conversion to hydrogen enables energy to be stored as gas and opens up the use of existing gas infrastructure



PROS	CONS
- Potential for valuable inter-seasonal storage; - Very high chemical energy per unit mass.	- Business case: competition with gas; - Capital costs; - CO_2 source availability; - Low round-trip efficiency.

- Power-to-gas uses electrons to produced methane, which can be sent to consumers through existing gas networks. Power is first converted to hydrogen through electrolysis, which is then either blended directly into the gas grid or synthetized with CO_2 to produce synthetic natural gas (SNG) through methanation.
- SNG's main advantage is that it can make use of gas infrastructure, getting round hydrogen's chicken-and-egg dilemma (whether it is necessary to build infrastructure in order to nurture demand or to create demand before building costly infrastructure). In Germany for instance, underground gas storage capacity is estimated to amount to 212 TWh and grid capacity close to 1,000 TWh/y compared with, respectively, 0.08 TWh and 500 TWh in the case of the power system. Therefore, even if blending is likely to be limited by safety and performance constraints to a rate of 5% to 20% of total volume (depending on system, end-uses, pipeline materials, injection point) this will represent huge storage capacity.
- Methane can also be passed through gas turbines, used in compressed natural gas vehicles or valorized for heat. This leads to the decompartmentalization of energy systems. However, power-to-gas faces strong competition from natural gas. Business cases may be difficult to justify in the short term as the technology is still developing and is subject to the availability of cheap CO_2.

Source: SBC Energy Institute Analysis; Specht et al. (2009), "Storing bioenergy and renewable electricity in the natural gas grid"

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Synthetic natural gas (SNG): fact card

KEY DATA

Installed capacity:	**~2 MW**	red
Power rating:	**kW - GW**	dark green
Discharge duration:	**Hours - Weeks**	dark green
Response time:	**sec - min**	light green
Efficiency:	**25 - 50%**	orange
Lifetime:	**30 years**	light green

High/fast → **Low/slow**

APPLICATIONS

Power fleet optimization
T&D deferral
Power quality
Black-start services
Intermittent balancing

Stronger application → **Limited application**

EXAMPLES

- E.ON Falkenhagen project: 2 MW electrolyzers supplied by excess wind power have been built to generate up to 360 m^3 per hour of hydrogen, which will be injected into the Ontras transmission gas network at a maximum pressure of 55 bar.

Note: Round-trip efficiency depends to a large extent on end-use (*e.g.* combined heat & power, combined cycle, but also power or heat applications).
Source: SBC Energy Institute Analysis; E.ON (2013), "Power to Gas – a promising solution to integrate large quantities of fluctuating renewable power"

3. Status & future development

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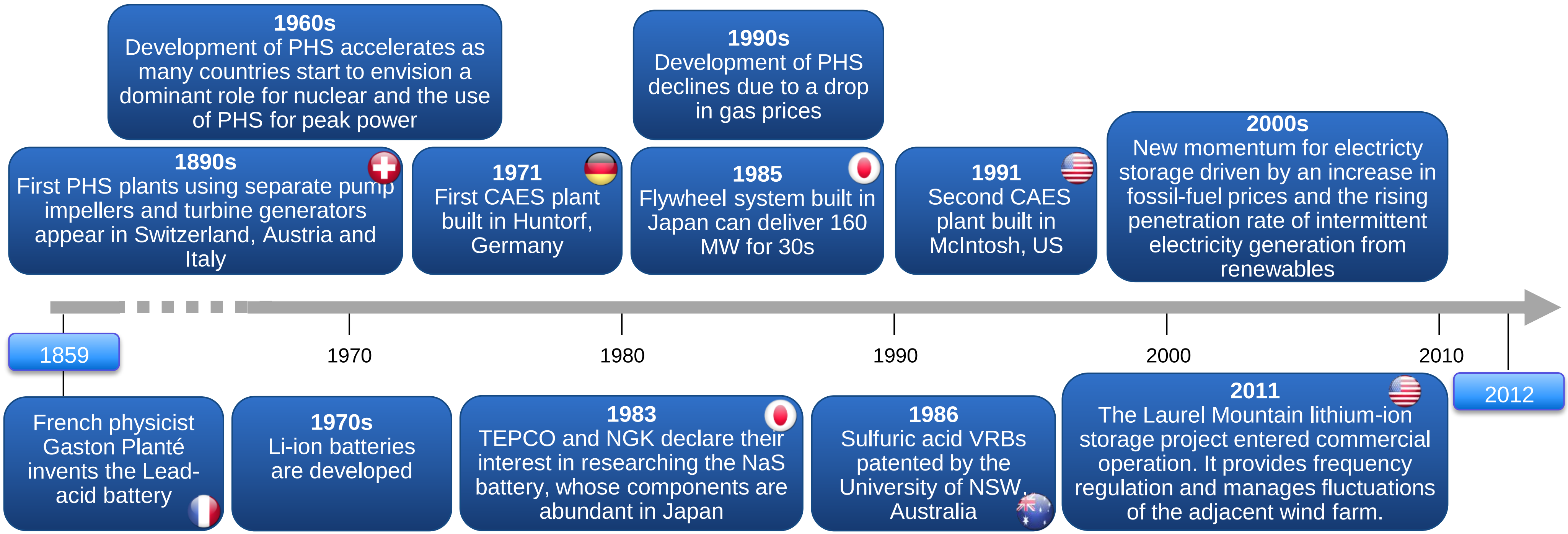
New technologies have continued to emerge since the invention of lead-acid batteries in 1859

ELECTRICITY STORAGE TIMELINE



Note: PHS: pumped hydro storage; CAES: compressed air energy storage; NaS: sodium-sulfur; VRB: vanadium redox battery, Li-ion: lithium-ion battery.
Source: SBC Energy Institute Analysis based on IRENA (2012), “Electricity Storage – Technology Brief”; Chi-Jen Yang (2011), “Pumped Hydroelectric Storage”

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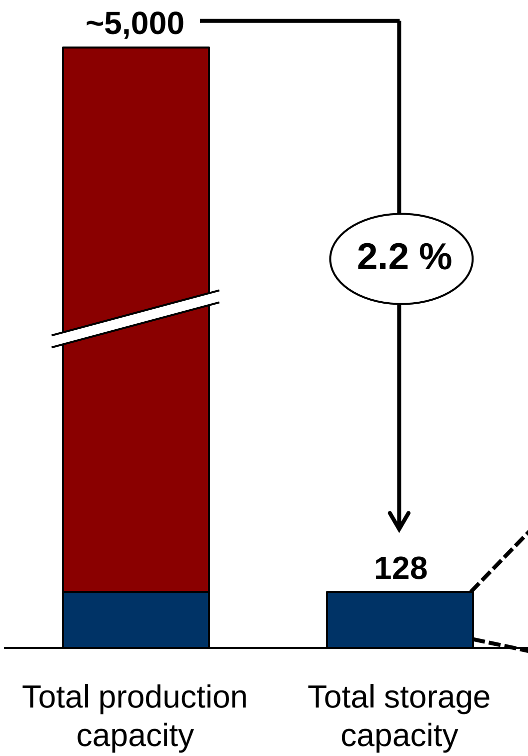
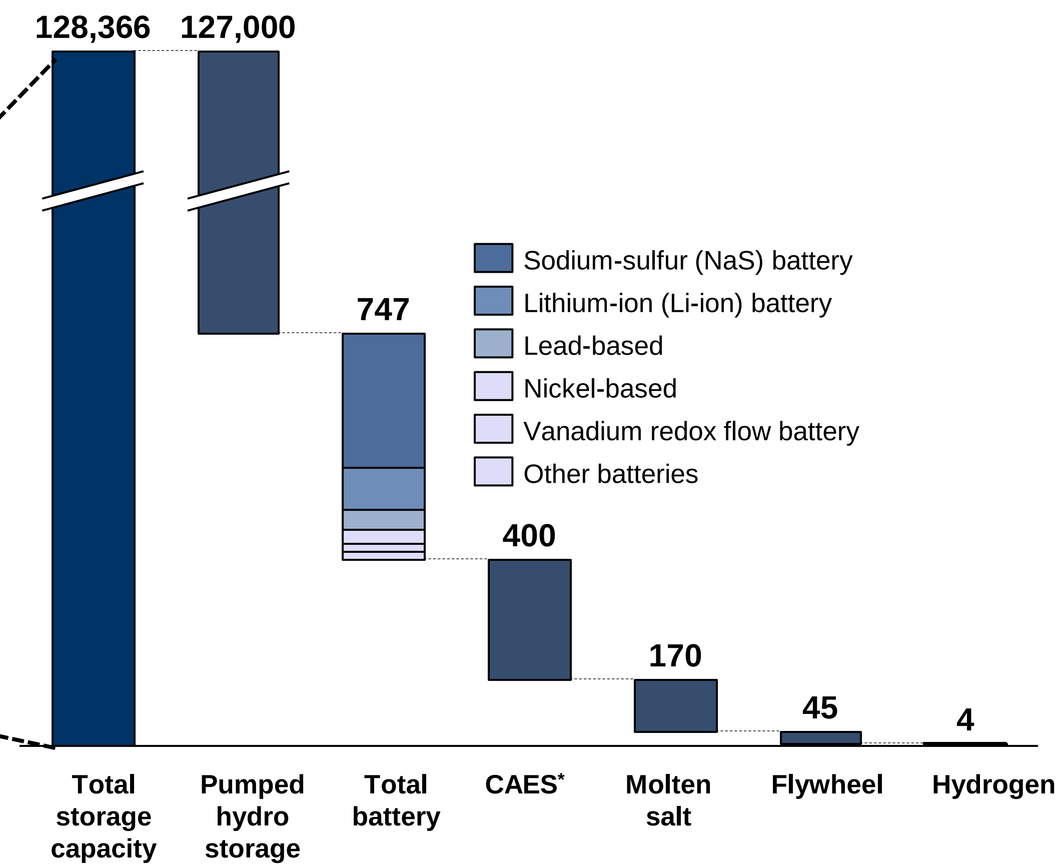
Worldwide storage capacity currently stands at 128 GW, 99% of which is pumped hydro storage

EXISTING WORLDWIDE STORAGE CAPACITY
GW, 2012



SHARE OF STORAGE CAPACITY BY TECHNOLOGY
MW, 2012



Note: * CAES: compressed air energy storage.
Source: SBC Energy Institute Analysis based on Bloomberg New Energy Finance database extracted on 12th April 2013; Jun Ying (2011); "The future of energy storage technologies and policy"

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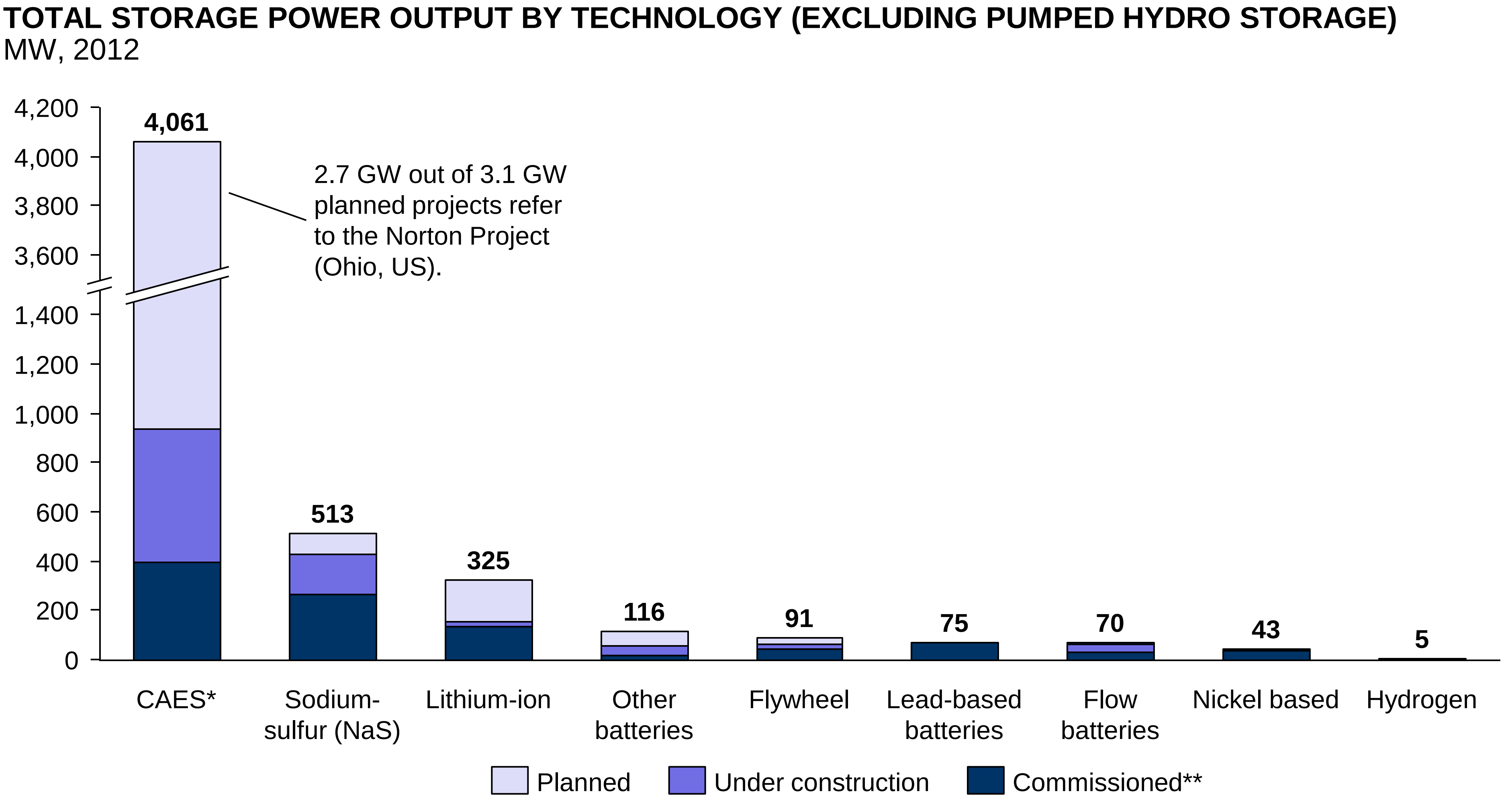
Compressed air energy storage (CAES) and conventional batteries continue to be the preferred alternative to pumped hydro storage



Note: * CAES: compressed air energy storage.
** Commissioned include commissioned and partially commissioned plants. Planned include announced/planned projects, as well as permitted plants.

Source: SBC Energy Institute Analysis based on Bloomberg New Energy Finance database extracted on 12th April 2013

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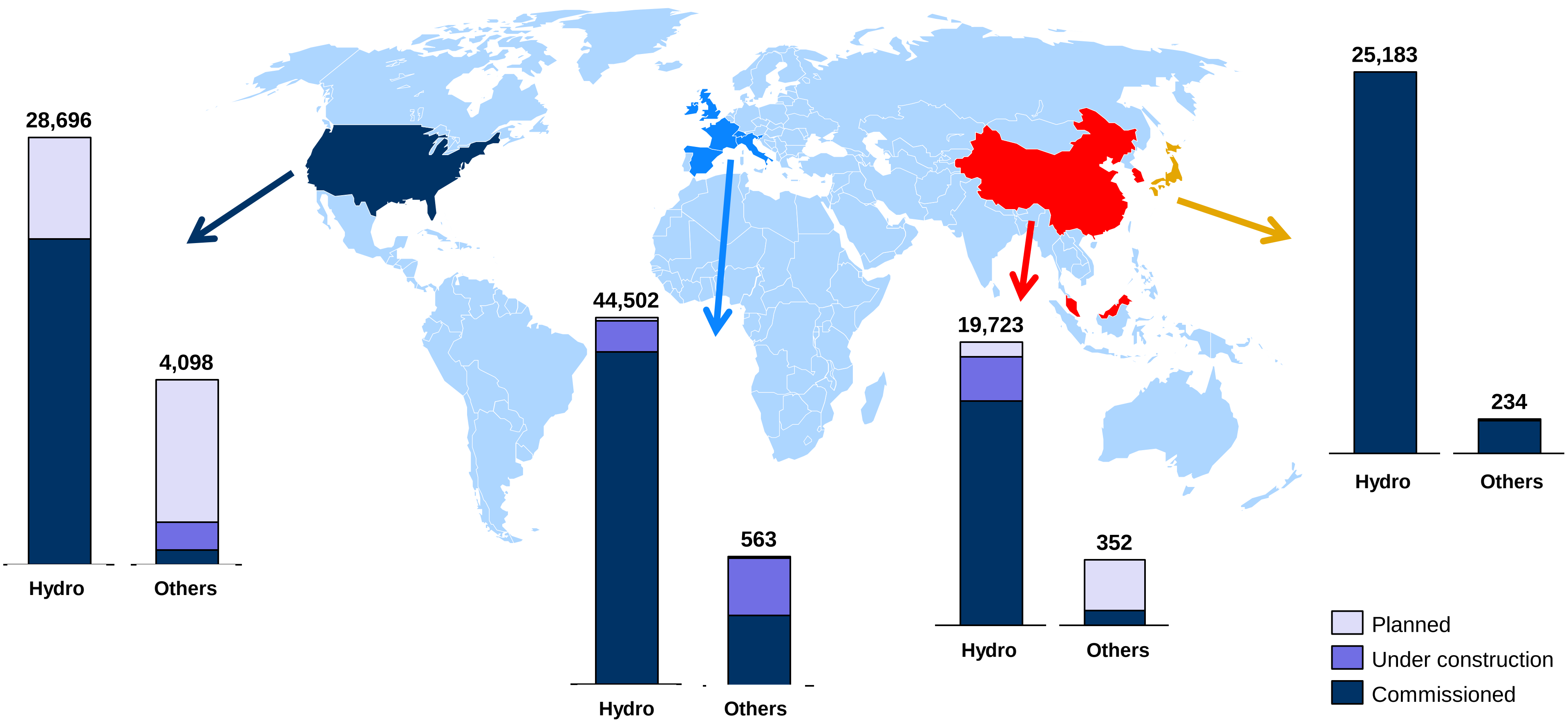
The US has undertaken many new projects and is seen as the new market leader

PUMPED HYDRO STORAGE AND PROJECTS USING OTHER TECHNOLOGIES
MW, 2012

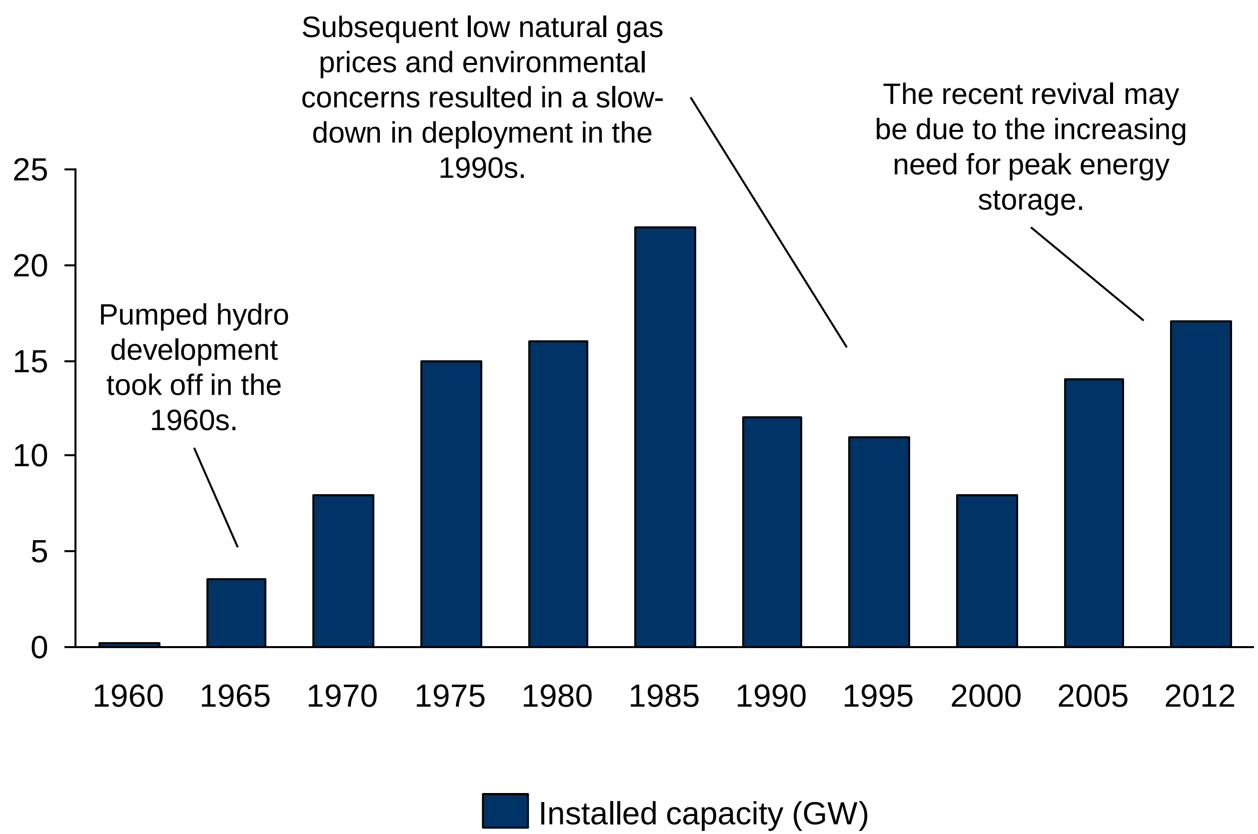


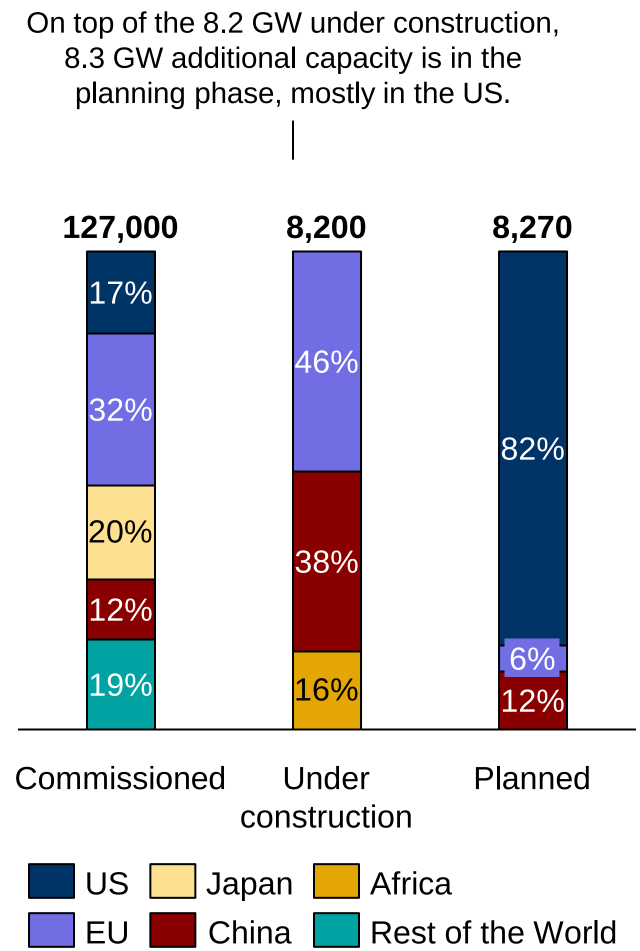
Note: Commissioned include commissioned and partially commissioned plants. Planned include announced/planned projects, as well as permitted plants.

Source: SBC Energy Institute Analysis based on Bloomberg New Energy Finance database extracted on 12th April 2013

The pipeline for pumped hydro storage is small compared with installed capacity

PUMPED HYDRO STORAGE DEPLOYMENT: OPERATIONAL & IN DEVELOPMENT
MW, 2012





Note: Commissioned include commissioned and partially commissioned plants. Planned include announced/planned projects, as well as permitted plants.
Source: SBC Energy Institute Analysis based on Bloomberg New Energy Finance database extracted on 12th April 2013

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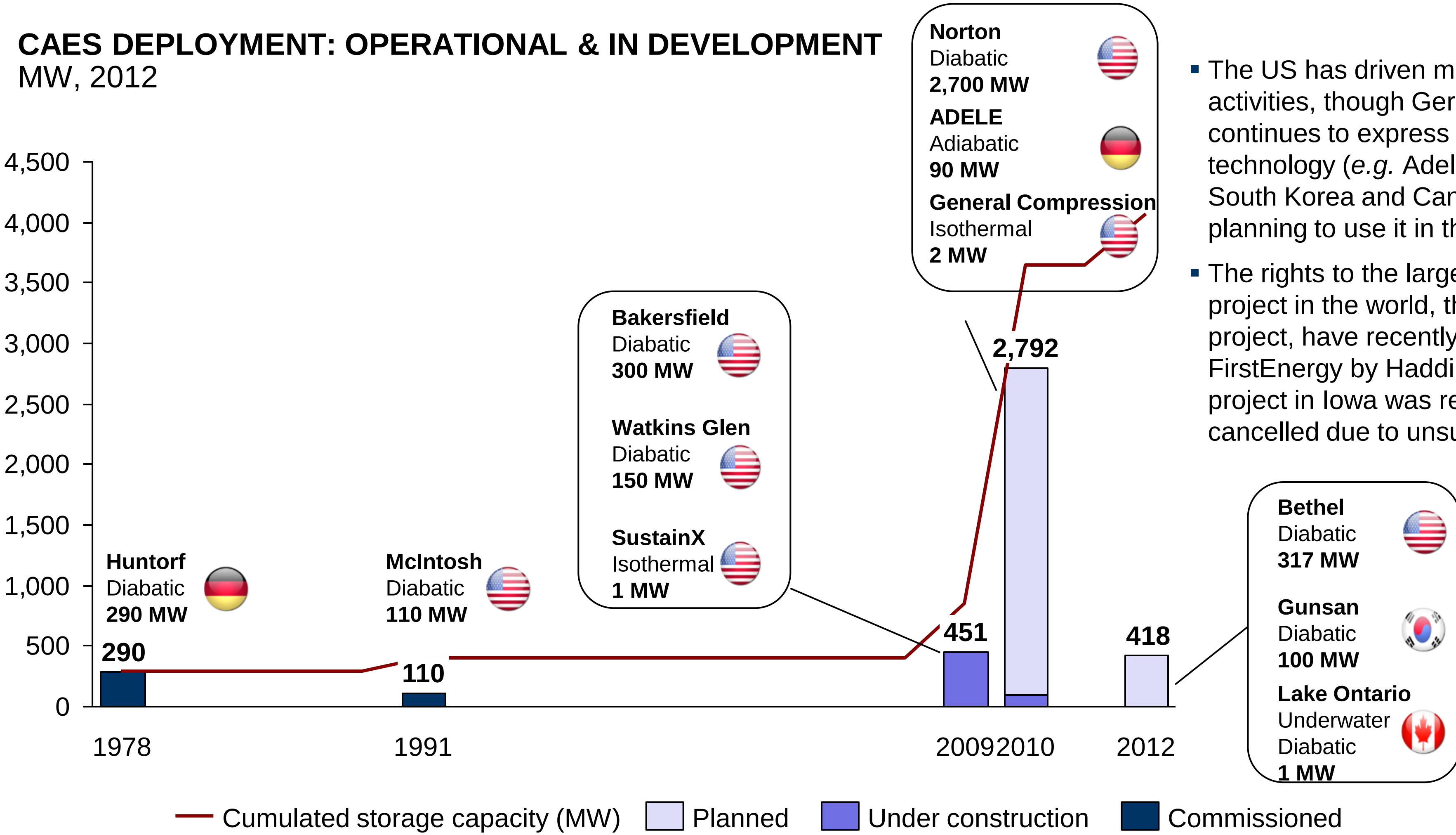
Compressed air energy storage (CAES) may take off in the next 5 years, driven by the US, but adiabatic and isothermal installations are still far from commercial

CAES DEPLOYMENT: OPERATIONAL & IN DEVELOPMENT
MW, 2012

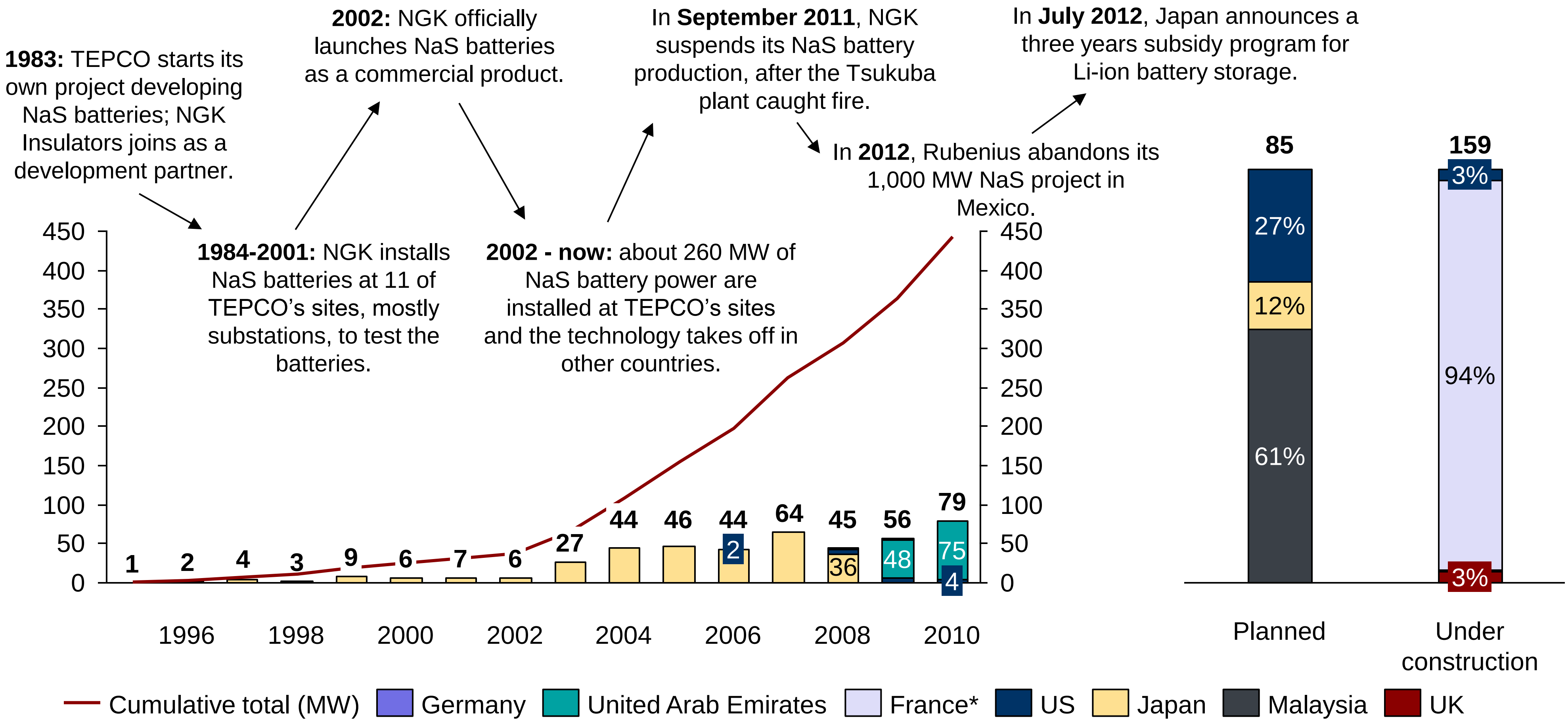


- The US has driven most CAES activities, though Germany continues to express interest in the technology (*e.g.* Adele project) and South Korea and Canada are planning to use it in the future.
- The rights to the largest CAES project in the world, the Norton project, have recently been sold to FirstEnergy by Haddington. A project in Iowa was recently cancelled due to unsuitable geology.

Note: Commissioned include commissioned and partially commissioned plants. Planned include announced/planned projects, as well as permitted plants.
Source: SBC Energy Institute Analysis based on Bloomberg New Energy Finance database extracted on 12th April 2013

Projected sodium-sulfur (NaS) battery capacity largely surpasses installed capacity and has a widespread geographical deployment

NAS DEPLOYMENT: OPERATIONAL & IN DEVELOPMENT
MW, 2012



Note: The 150 MW in France relate to an agreement signed between NGK and EDF Energy Nouvelles in 2009. Batteries were aimed to be used primarily for photovoltaic systems, especially in French overseas territories, with a first 1 MW plant commissioned in La Réunion.

Source: SBC Energy Institute Analysis based on Bloomberg New Energy Finance database extracted on 12th April 2013

Lithium-ion batteries seem to be taking off, whereas flow batteries may need a little more time

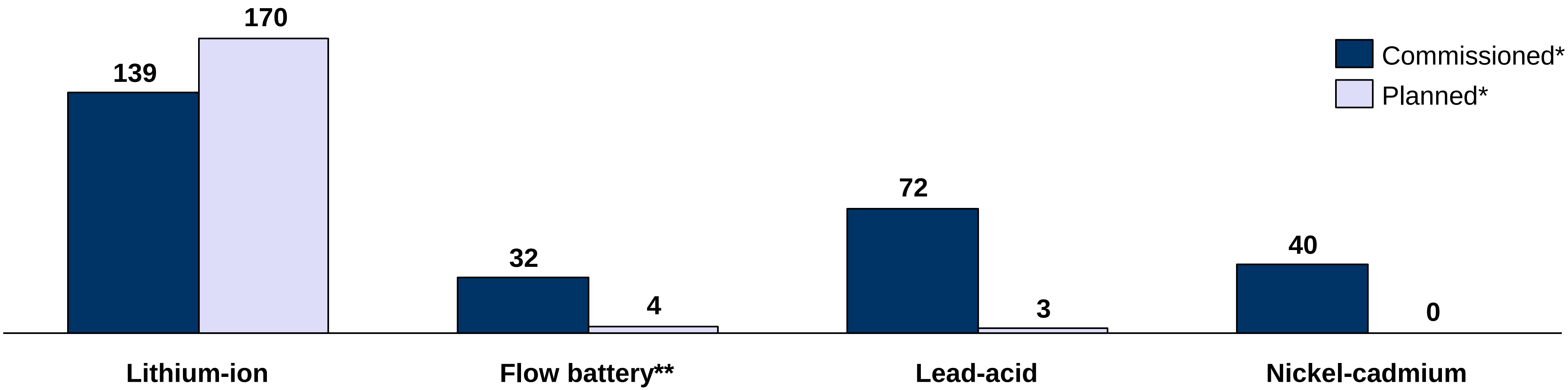
BATTERY PROJECTS: OPERATIONAL & SHORT TERM PIPELINE
MW, 2012

- Li-ion projects have increased in popularity in the last 2 years.
- They are the favored method of electricity storage in China, and Japan just announced a three-year subsidy program.

- Flow technology is at an early stage of development compared with other battery technologies.
- Therefore, growth over the next few years may be slow
- However, many predictions show it overtaking both li-ion and NaS by the end of the decade.

- Lead-acid is the oldest battery type and presents limited potential for growth.
- Recent improvements in carbon-electrode and supercapacitor technology could give lead-acid a new lease of life.

- Nickel-cadmium (Ni-Cad) is not explored in this study as installed capacity is very small and there are few projects in development.

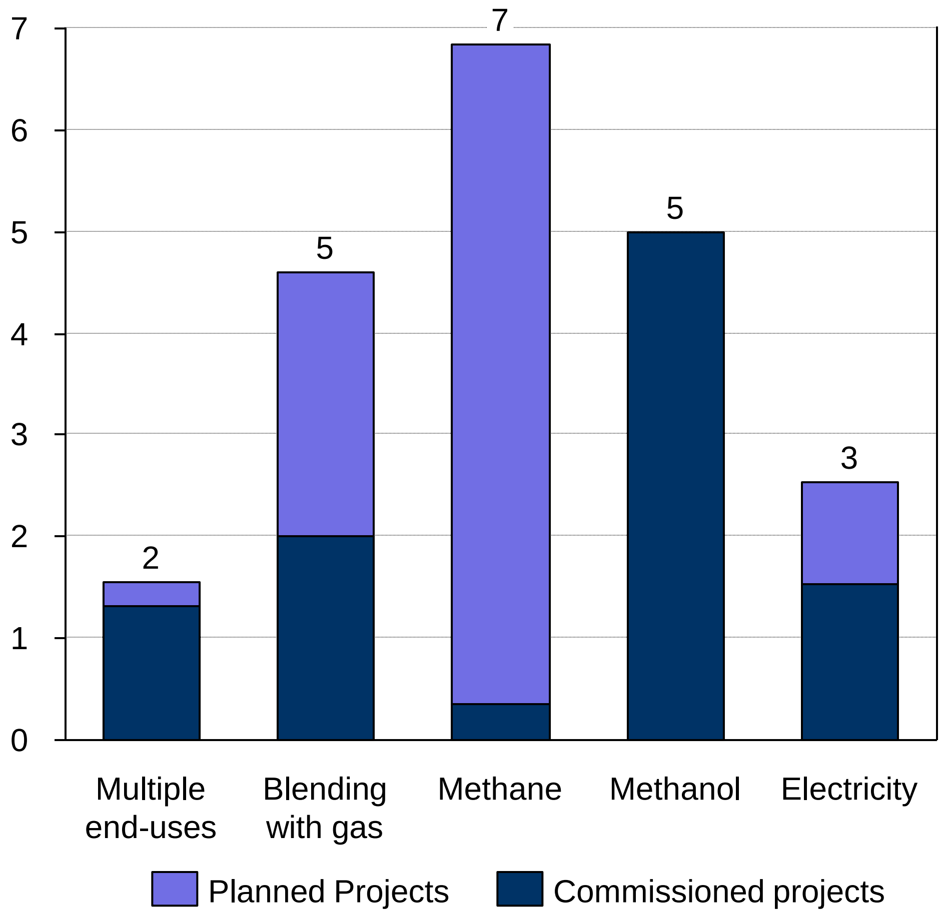


Note: * Commissioned include commissioned and partially commissioned plants. Planned include announced/planned projects, as well as permitted plants.
** More projects are likely to be planned in China, but haven't been disclosed and are consequently not included in figures above.

Source: SBC Energy Institute Analysis based on Bloomberg New Energy Finance database extracted on 12th April 2013

Hydrogen and synthetic natural gas storage technologies are at the early demonstration phase

HYDROGEN STORAGE PROJECT CAPACITY BY END-PRODUCT
MW



- Chemical storage projects are in the early demonstration phase, with 8.6 MW of commissioned capacity and 12.7 MW of planned capacity. Commissioned capacity consists of 43 small projects*, 8 in Germany, 6 in the US and 4 in the UK. Planned capacity is characterized by an increase in size as it includes only 11 projects. More than half of these (6) are located in Germany, the main proponent of hydrogen storage.
- Chemical storage is part of the re-electrification pathway, in which electrical power that was used for electrolysis and stored as hydrogen is converted back into electricity. However, development seems to be at standstill, with the number of projects limited and mostly small in scale. Furthermore, power-to-gas applications (injection into the gas grid or methanation) seem to be taking the lead, with large-scale demonstration plants operating in Germany and the UK.

Note: * 13 of the 43 projects commissioned have shut down.
Source: SBC Energy Institute analysis; Gahleitner (2013) for data prior to 2013

Electricity storage is gaining momentum, with roadmaps under development at the national and international levels

EXAMPLES OF PLANS AND ANNOUNCEMENTS

iea	The International Energy Agency launched a new Technology Roadmap in February 2012 that will set milestones and targets for storage, guided by the Agency's decarbonization scenarios.
	The European Union's Energy Roadmap 2050 acknowledged the importance of electricity storage, but did not specify any targets. Clarification is expected as part of the continuing consultation for the 2030 framework. The European Association for the Storage of Energy released its own roadmap in April 2013
	A month after his nomination, US Energy Secretary Ernest Moniz confirmed that electricity storage is a priority and committed to releasing a formal timeline for a plan for electricity storage.
	George Osborne, UK Chancellor of Exchequer, identified electricity storage as one of the eight technologies in which UK should become world-leader: *"greater capability to store electricity is crucial for these [intermittent] power sources to be viable. It promises savings on UK energy spend of up to £10bn a year by 2050 as extra capacity for peak load is less necessary."*
	In 2011, South Korea announced that it would invest $5.94 billion by 2020 in developing the energy-storage industry - one third on R&D and the rest on building infrastructure. The government will participate along with private companies.

- Unlike renewables, smart meters or carbon capture & storage, there is currently no target for electricity storage development and virtually no technology roadmap, except those developed by industry associations.
- Driven by the recent surge of intermittent renewables and the difficulty experienced by electricity storage to develop in the current regulation and economic framework, several roadmaps are under development. These roadmaps are expected to identify R,D&D gaps and barriers to development (*e.g.* on the regulation side, ownership of storage plants), as well as to agree on development milestones and to promote business cases.

Source: IEA (2013), "IEA Energy Storage Technology Roadmap Initial Stakeholder Engagement Workshop Proceedings"; EASE/EERA (2013), "European Energy Storage Technology Development Roadmap towards 2030"; Guardian (2012), "George Osborne: make UK a world leader in energy storage"; China.com (2011), "S Korea to invest 5.9 bln USD in energy storage industry"; Electricity Storage Association (2013), "Energy secretary nominee Moniz to announce storage timeline soon after confirmation"

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Research, Development & Demonstration

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R,D&D priorities vary according to the technology

SUMMARY OF MAIN DRIVERS OF R,D&D AXIS BY TECHNOLOGY

TECHNOLOGY		DRIVERS	AXIS OF R,D&D
1 PUMPED HYDRO STORAGE		– Facilitate intermittent integration – Sidestep site availability issues	– Upgrade old facilities (*e.g.* variable-speed turbines) – Develop alternative reservoirs (seawater or artificial underground, underwater and aboveground)
2 COMPRESSED AIR ENERGY STORAGE		– Avoid/limit natural gas use – Sidestep site availability issues	– Avoid heat losses upon compression (adiabatic, isothermal and hybrid concepts) – Develop alternative reservoirs
3 BATTERIES		– Increase power & energy density – Lower costs & increase lifecycle – Reduce environmental impact	– Develop lower-cost materials and chemistries – Improve performance of current chemistries – Reuse electric-vehicle batteries for electricity storage
4 HYDROGEN & SYNTHETIC NATURAL GAS		– Adjust hydrogen technologies to intermittent needs (production, storage, end-uses)	– Enhance performance & lower costs of electrolysis – Develop underground and solid storage – Investigate power-to-gas and power-to-liquid

Source: SBC Energy Institute Analysis

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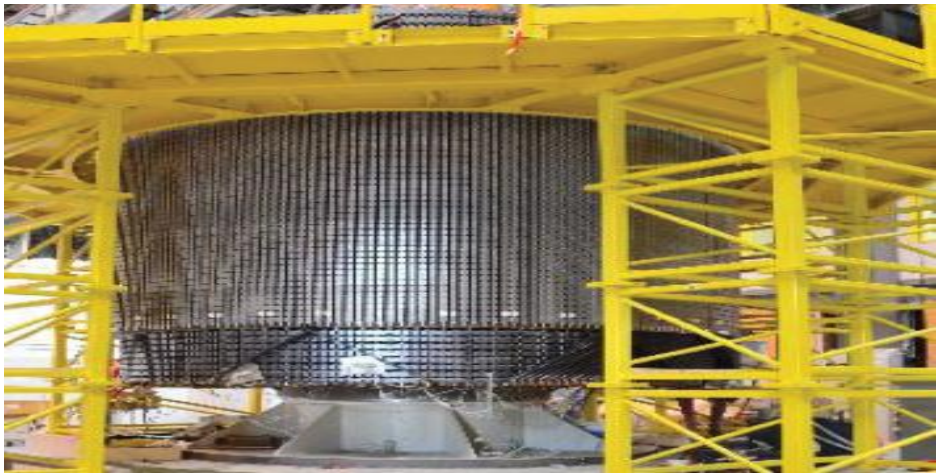
R,D&D efforts are aimed at increasing the flexibility of pumped hydro storage (PHS) in order to support intermittent renewable integration

VARIABLE SPEED TURBINE



Variable-speed turbines use an asynchronous motor-generator to adjust the rotational speeds of the pump and turbine .

Its benefits include:

- *Efficiency*: Increased pump-turbine efficiency (~1%)
- *Reliability*: Avoid operation modes subject to hydraulic instability or cavitation to increase durability
- *Flexibility*: faster power adjustment to respond to grid requirements and operate part load pumping, allowing pumped hydro storage to help regulate voltage and frequency (low load).

- **Upgrading opportunities**: a significant proportion of pumped hydro storage plants are aging, notably in Europe, where 80% were commissioned before 1990, and in the US where the last plant was completed in 1995. These plants were not primarily designed to help balance intermittent renewables, but rather to maximize baseload generation (price arbitrage, meet peak demand). R,D&D is therefore under way to upgrade these plants to make them better equipped to respond to the intermittency challenge of renewables by increasing response time in new plants (<15 second).

- **Drivers of R,D&D:**
  - *Increase efficiency*: from 60% to 85% thanks notably to variable-speed turbines whose efficiency is closer to optimal efficiency;
  - *Increase reliability:* by using stronger core components (*e.g.* thrust bearing and oblique elements in the motor) and improved control systems (software, redundancy…);
  - *Increase flexibility:* faster power adjustment to absorb excess power, thanks notably to variable-speed turbines.

- **Variable and single-speed turbines**: variable-speed turbines are the focus of R,D&D for pumped hydro storage. Developed in Japan (395 MW installed in 1993 in Kansai unit 2), the technology provides increased flexibility, efficiency and reliability, but increases costs (notably, greater excavation is needed due to a longer shaft).

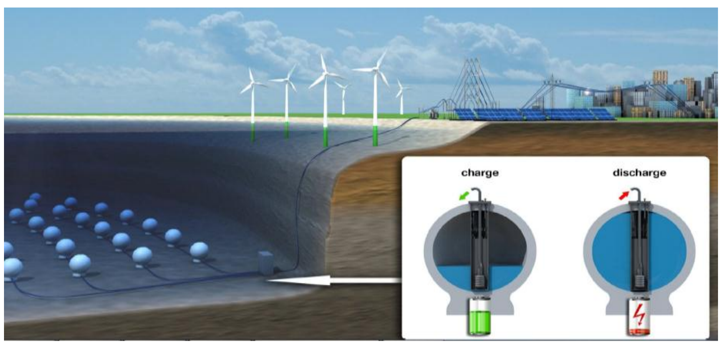
Source: Alstom (2012), "Pumped hydro Storage Plants"; Chi-Jen Yang (2011), "Pumped Hydroelectric Storage"

Alternative pumped hydro storage reservoir types are also being developed to sidestep the constraint of site availability and minimize environmental impacts

ILLUSTRATION OF ALTERNATIVE PHS RESERVOIR

SEAWATER PHS

UNDERWATER PHS



- **The biggest challenge to establishing pumped hydro storage (PHS) is to find suitable natural sites, notably for lower reservoirs.** Using rivers is not necessarily the best option as dams have to be erected, changing the water level, which raises safety and environmental issues. R,D&D is focused on developing alternative reservoir types, notably underground (as opposed to the current overground solutions), storing sea water instead of freshwater and innovating sea-based solutions.

- **Seawater PHS** uses seawater in the lower reservoir. This simultaneously increases the number of suitable locations for PHS, and eliminates concerns over fresh water use. This solution is the most mature alternative to conventional PHS and draws from the experience of the 30 MW Yanabaru Okinawa PHS station commissioned in 1999 in Japan. Ireland and Hawaii have also announced their interest in seawater PHS, planning 480 MW and 300 MW projects respectively.

- **Underground PHS (UPHS)** has been contemplated since the 1970s, though no large-scale projects have yet been developed and economic feasibility has not been demonstrated. Underground PHS consists of drilling a well and galleries at the bottom of the top reservoir to use as an underground lower reservoir, with an integrated pump/turbine at the surface or just below the upper reservoir. Such a system could allow distributed small-to-medium-scale applications (avoiding large excavations). Underground PHS may be increasingly used thanks to advances in excavating techniques and computer modeling. Gravity Power is already developing a 40 MW facility with 4 hours of storage.

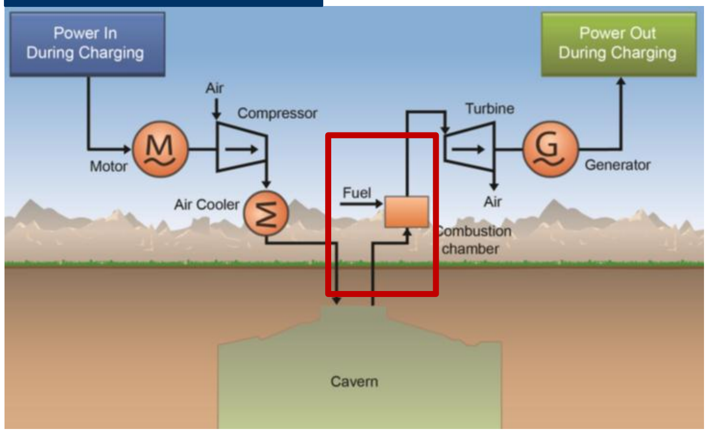
- **Alternative sea-based solutions:** underwater PHS (Stensea project) pumps water into 30-meter diameter spheres anchored at the seabed, which can store up to 20 MWh each. Another sea-based alternative solution was proposed in Belgium.

Source: Hochtief (2012), "Annual Report"; Gravity Power (http://www.gravitypower.net)

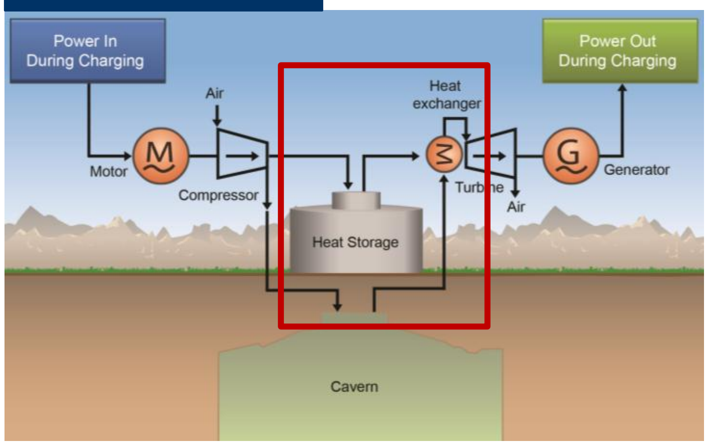
Several new compressed air energy storage (CAES) concepts are under development to reduce or avoid gas use and thereby increase system efficiency

CONVENTIONAL *VS.* ADIABATIC CAES

DIABATIC CAES



ADIABATIC CAES



- **Compressed air energy storage R,D&D is largely focused on tackling the reliance on fossil fuels, usually gas, to heat the air during expansion.** Limiting or avoiding gas use has the potential to increase system efficiency (to up to 70%) and limit CO_2 emissions. More than energy storage devices, current CAES facilities are essentially gas turbines that consume 40% to 60% less gas than conventional turbines. Two main alternatives to the conventional type are being investigated: Adiabatic CAES and Isothermal CAES.

- **Adiabatic CAES** consists of storing waste heat from the air-compression process and using instead of gas to heat up the air during expansion. Although thermal storage is already used in concentrating solar power plants*, it is still commercially challenging, especially for high temperatures that require specially adapted components. Several options (oil, molten salts, concrete…) are being investigated. Currently, there are no adiabatic plants in operation, but several projects have been launched including RWE's 90 MW Adele projects. Hybrid designs, which include both heat storage and gas use, or low temperature CAES - which uses water as a heat storage medium but requires more energy for compression - are also being explored, notably by E.ON in Germany.

- **Isothermal CAES** consists of compressing the air while continuously removing and storing the by-produced heat to maintain a constant temperature. The stored heat is then used during expansion for the same purpose. SustainX is developing solutions in which water is continuously sprayed into the cylinder containing the air to absorb the heat during compression, and this same water is then used to transfer back heat during expansion. A pilot plant of 1 MW is under development in New Hampshire, USA**.**

Note: * For more information on thermal storage, you can refer to the concentrating solar power FactBook recently published by the SBC Energy Institute.
Source: RWTH Aachen (2012), "Review of Energy Storage Options"; E.ON (2012), "Compressed Air Energy Storage – one promising technology in the future energy storage business"; SustainX (http://www.sustainx.com/)

Artificial compressed-air energy-storage reservoirs are being developed in response to the limited availability of natural storage formations

ALTERNATIVE RESERVOIRS

PRESSURIZED TANK

UNDERWATER BAGS

- **Compressed air energy storage projects usually use underground salt caverns as a storage vessel** (either man-made or abandoned mines). Salt caverns have the advantage of being gas-tight (no depletion) and of being able to handle frequent charging and discharging cycles*. The two CAES plants currently operated by Huntorf and McIntosh make use of salt formations.
- **However, salt deposits do not necessarily occur in the desired electricity storage locations**. Furthermore, unlike hydrogen or natural gas, CAES can only be operated over a depth of 500 meters to 1,300 meters since operating pressure depends on depth and state-of-the-art components operate at pressures of 50 bar to 100 bar.
- **Therefore, artificial pressurized reservoirs are being investigated.** The rationale behind artificial reservoirs is to operate at constant pressure instead of at constant volume, as is the case in salt caverns. For example, 20 meters diameter underwater bags developed by Thin Line Aerospace could store about 70 MWh at a 600-meter depth. More conventional aboveground pressurized tanks are also being developed by SustainX and LightSail for their isothermal technologies, allowing for decentralized CAES Plants.

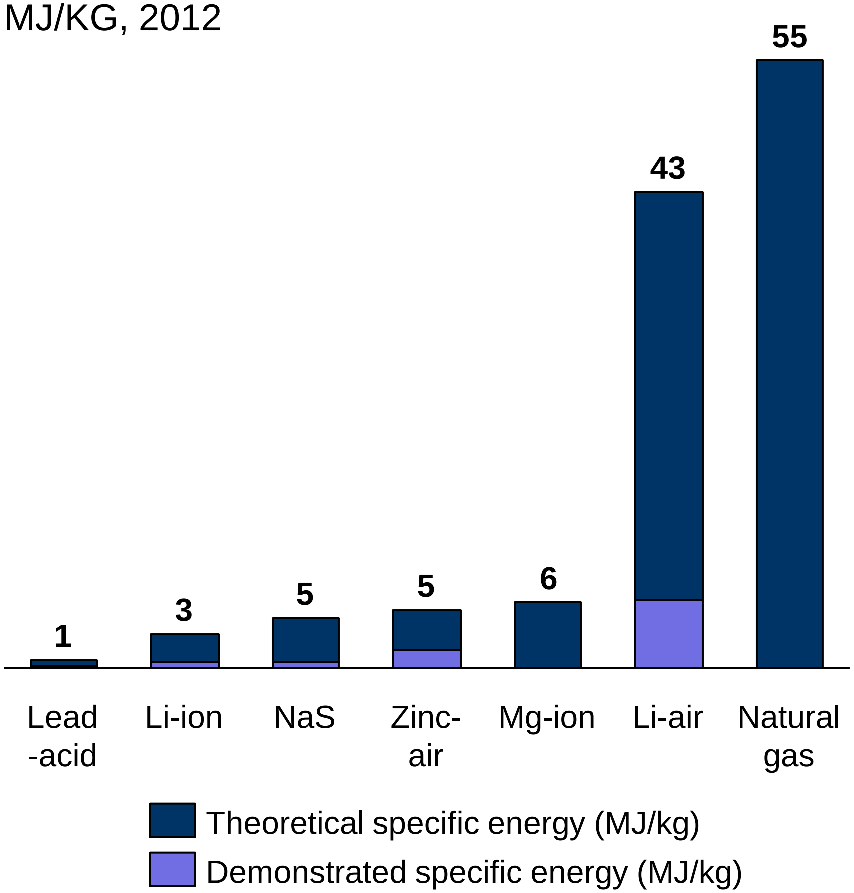
Note: * The flexibility of salt caverns regarding withdrawal and injection rates as well their low cushion gas requirement has made them an attractive means of storing natural gas over the last decade.

Source: SBC Energy Institute Analysis based on Thin Red Line Aerospace (http://www.thin-red-line.com/); Lightsail Energy (http://www.lightsail.com/)

Lower costs, and higher durability chemistries and materials are the priorities of battery-storage R,D&D

THEORETICAL SPECIFIC* ENERGY LIMITS BY TECHNOLOGY

MJ/KG, 2012

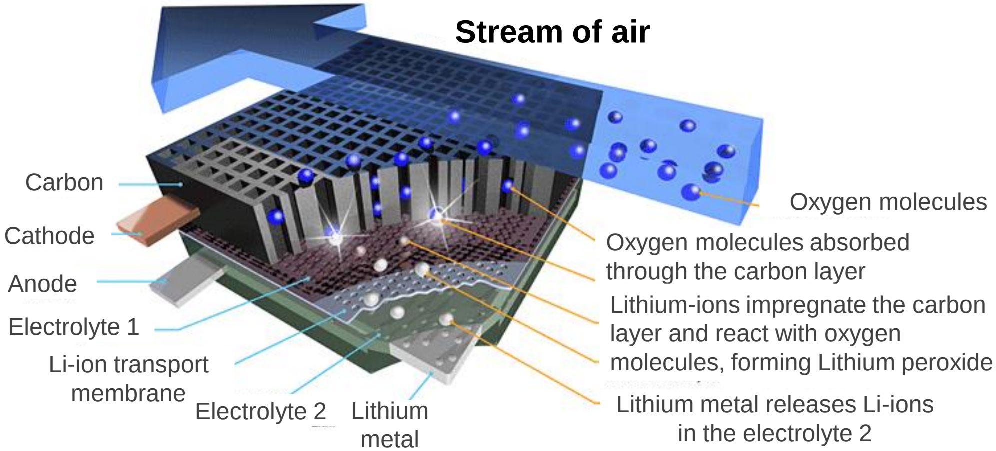


- **R,D&D is focused on tackling batteries' main drawbacks**: low energy and power density, poor cycle life, high costs and safety and environmental challenges. Two axes are being investigated: *1/* new material to improve current technologies and *2/* new chemical composition for alternative battery types.
- **For existing battery technologies, priorities and levers are highly specific:**
  - **Lithium-ion:** find lower-cost materials for the negative electrode (*e.g.* air, titanium oxide) to increase energy density and cycle life;
  - **Lead-acid**: Improve cycle life and depth of discharge;
  - **NaS**: tackle safety issues and high temperature range that limit their applications;
  - **Flow batteries:** replace water-based electrolyte with organic solutions to improve specific energy and cycle life.
- While there is room to bridge the gap between the demonstrated and theoretical specific energy of existing technologies, R,D&D is also trying to identify alternative electrochemical solutions that would achieve higher energy density:
  - **Metal-air**: use oxygen at the cathode avoiding storing one of the components (*e.g.* Lithium-air);
  - **Multivalent-ion**: use materials like magnesium or aluminum that have two or three electrons available for the chemical reaction, which theoretically means two or three times more energy.

Note: * Specific energy is defined as the amount of stored energy per mass unit.
Source: Kurt Zenz House (2009), "The limits of energy storage technology"

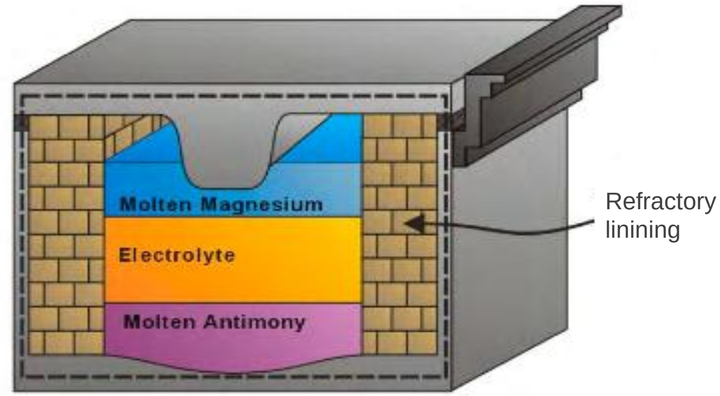
Lithium-air batteries are being investigated as a replacement for lithium-ion technology, while liquid-metal batteries are promising for grid-scale storage

METAL-AIR BATTERIES



- **Metal-air batteries are being investigated to reduce battery costs and increase their energy density**. They use (di)-oxygen (O_2) at the cathode, eliminating the need to store one of the components (Oxygen, which is found in ambient air) and the need for a cathode structure.
- **The anode is a commonly available metal with a high energy density that releases electrons when oxidized.** Many metals including zinc and sodium, were considered but lithium prevailed (Li-Air) due to its low atomic mass, its superior oxidation ability and its relatively low cost.
- **Despite recent advances in material properties, li-air is still at an early stage of R&D** and its operation remains challenging due to the degradation that can occur at the cathode (*e.g.* humidity) and anode (corrosion).

LIQUID-METAL BATTERIES

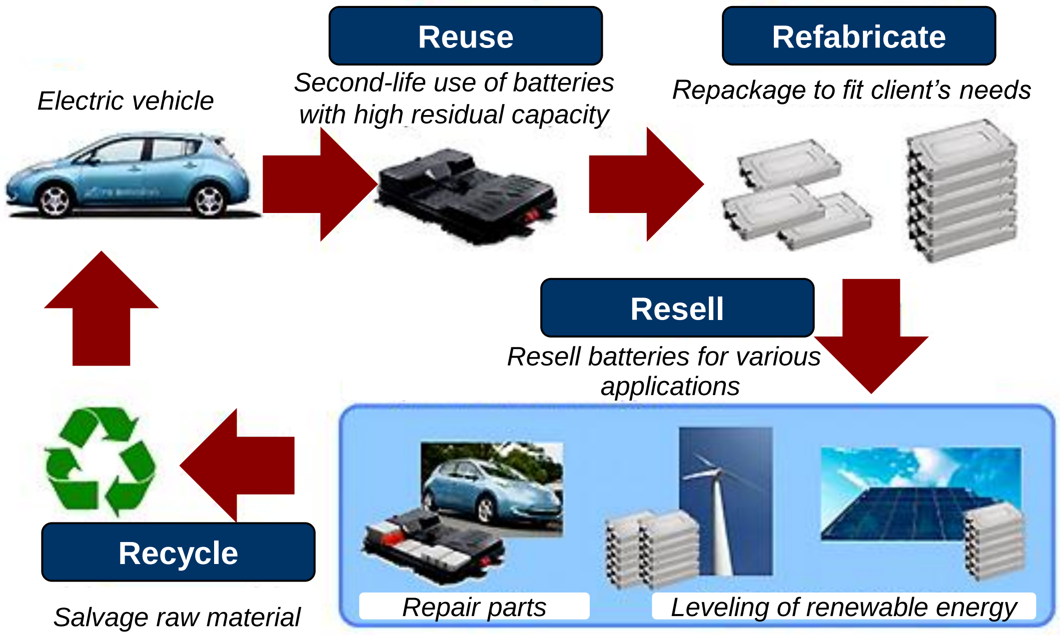


- **Conventional batteries use at least one solid material**. This solid material limits conductivity, increasing the risk of failure and as a consequence impacting the lifetime of batteries. R,D&D is turning to liquids to avoid using solid materials.
- **The liquid-metal battery, invented at MIT, uses two layers of liquid metals and a salt (electrolyte)**, which lie one on top of the other because of their differences in density. During discharge, the liquid metals release two electrons to form an ion that travels through the electrolyte to form an alloy at cathode (and the reverse happens upon charging).
- This technology is simple to assemble and relies on inexpensive materials, but requires high operating temperatures to keep the metals in a liquid state, which makes it more suitable for large-scale grid storage.

Source: Ambri (2013), http://www.energystorageexchange.org/projects

Giving electric vehicle (EV) batteries a second life by using them for electricity storage would reduce costs and environmental impact

LIFECYCLE OF AN ELECTRIC VEHICLE BATTERY WITH A SECOND LIFE



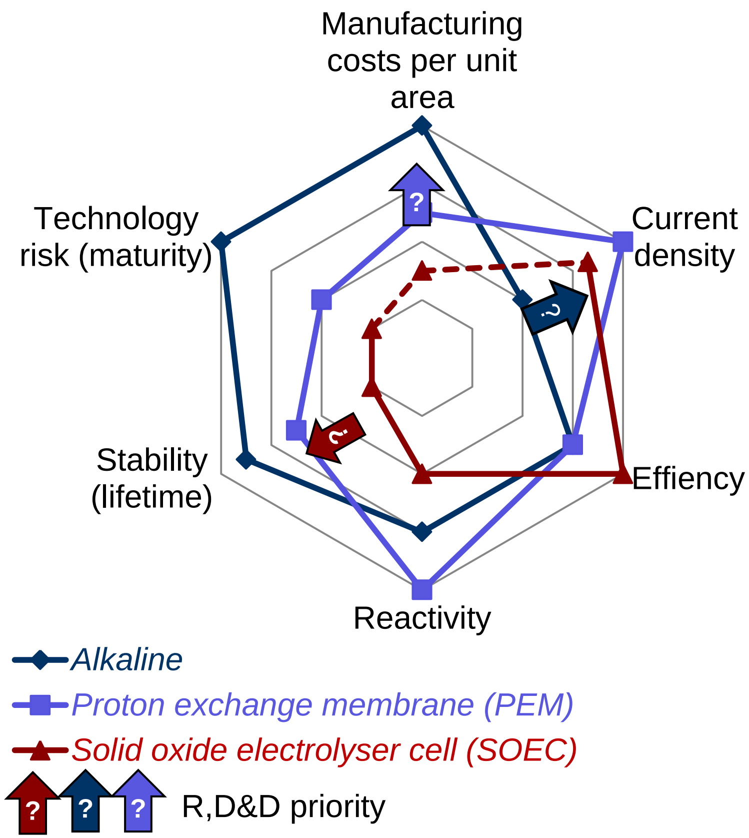
Examples of second-life applications

- If electric-vehicle (EV) deployment is to be the answer to meeting international scenarios on climate change, it would lead to a very significant volume of batteries. Although uncertainties on the chemistries that will dominate the market remain, Lithium-ion (li-ion) batteries account for fair share of the most recent developments due to their high energy density.
- Nonetheless, Li-ion batteries suffer from a short cycling life of 5 to 10 years, after which time they approach 70% of their initial capacity, which is too low to allow driving. The ultimate end of life is estimated at around 50% of initial capacity, so batteries unfit for vehicular use would still have a few years of life left that is suitable for stationary applications which have lower cycling requirements. This would not only lower the cost of batteries, but also minimize the environmental challenge of battery recycling.
- The economic feasibility of this course of action has not yet been proven, and some technical issues concerning reconditioning could also be raised since EV batteries are not standardized and will probably never be. However, several energy players and car manufacturers are considering this option. For instance, ABB has launched a first project to re-use Nissan batteries in order to build 50 kWh of storage.

Note: EV: electric vehicle
Source: Ademe (2011), "Study on the second life batteries for electric and plug-in hybrid vehicles"

R,D&D is under way to lower the cost of hydrogen electrolysis, promote new end-uses and demonstrate the feasibility of large-scale projects

COMPARATIVE ELECTROLYZER
- **TECHNOLOGIES**



- Hydrogen R,D&D has long been focused almost exclusively on answering demand side requirements (*i.e.* fuel cells, storage for mobility and combined heat and power applications), but is turning towards the supply-side to find a sustainable way to produce clean hydrogen from renewable power. The dominant focus of R,D&D is water electrolysis. R,D&D is also being conducted into laboratory-stage production technologies, such as direct production from bioenergy or solar energy (photolysis), and high-temperature thermo-chemical processes from nuclear.

- R,D&D into electrolysis seeks to improve performance (efficiency, lifetime, response-time), reduce costs (new materials) and demonstrate the feasibility of large scale plants. It explores ways of improve mature alkaline electrolyzers by developing new membranes or pressurized concepts reducing the costs of polymer exchange membrane (PEM), electrolyzers (*e.g.* new catalysts with cheaper material, new engineering processes) and high temperature solid oxide electrolyzers cells (SOEC).

- R,D&D is also working to assess the suitability of large scale underground storage in geologic formations* (salt formation, underground oil & gas** fields, deep aquifers) and to develop metal hydrides for hydrogen absorption. It also seeks to demonstrate the feasibility of large hydrogen storage solutions and investigates multiple end-uses (re-electrification of stored hydrogen, but also power-to-gas by injecting hydrogen into natural gas grids, or synthetizing methane in methanation processes*).

Note: * For more information, please refer to SBC Energy Institute report on hydrogen-based storage solutions.
** Cooperative projects for energy storage in depleted oil & gas field could be developed in partnership with oil & gas producers, notably in the Middle East & North Africa.

Source: SBC Energy Institute analysis

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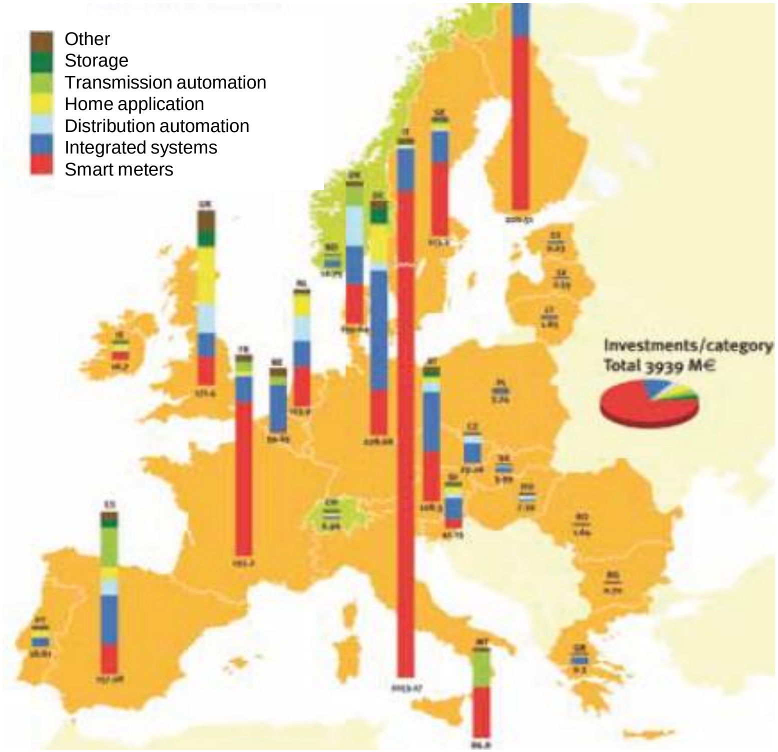
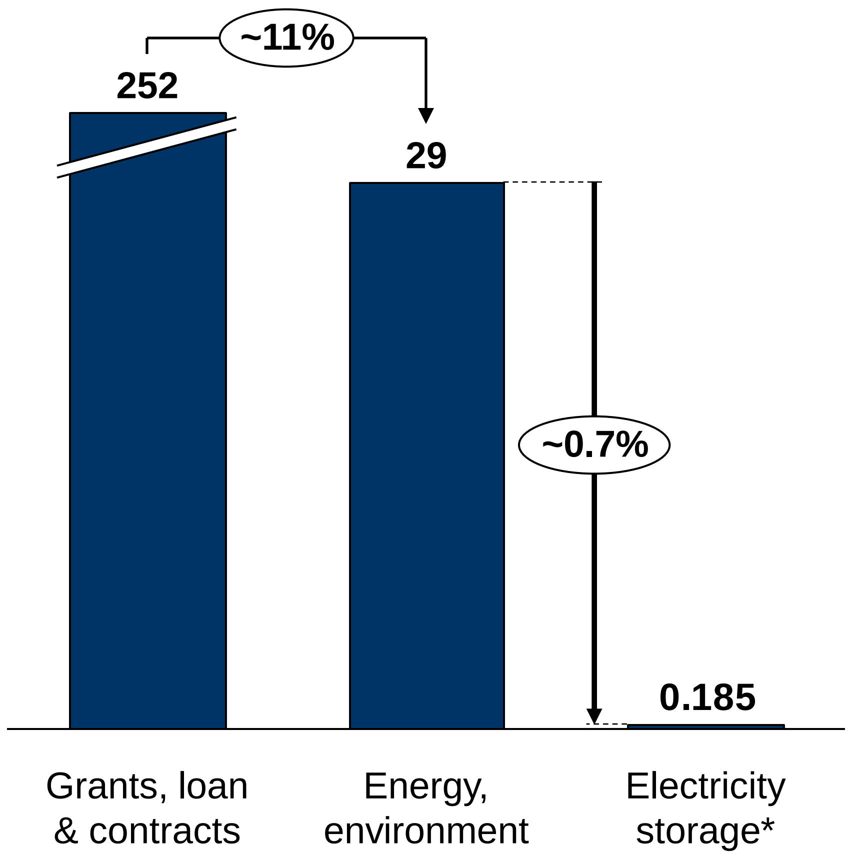
Electricity storage R&D funding is lagging behind that of other energy and environment projects

EUROPEAN ENERGY PROJECTS
€ million



The number of storage projects is negligible compared with the number of smart grids and other clean energy projects

US RECOVERY ACT FUNDING
$ billion

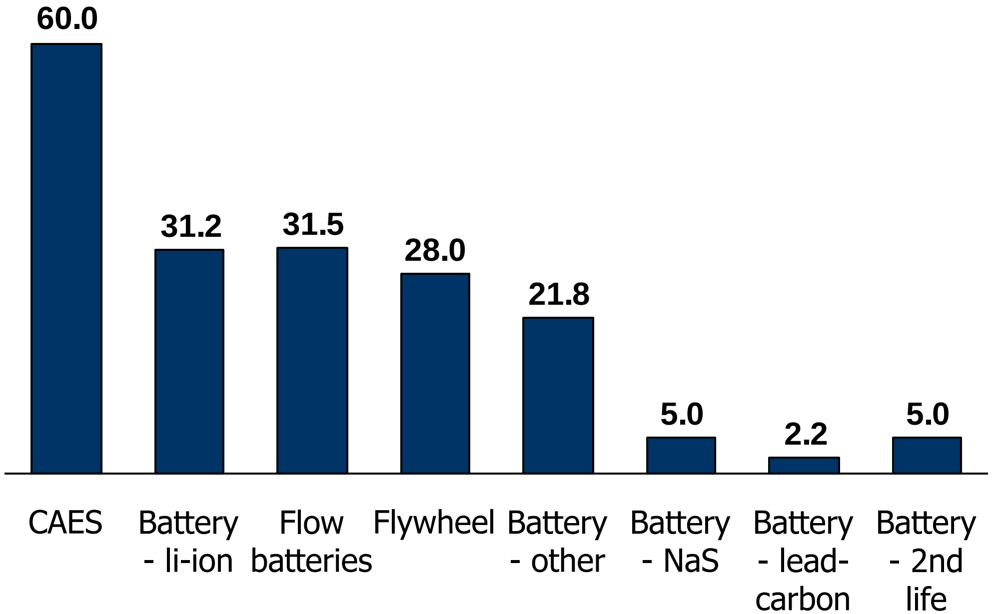


Note: * This number refers to the main US Department of Energy award given in 2009, details of project repartition are shown next slide.

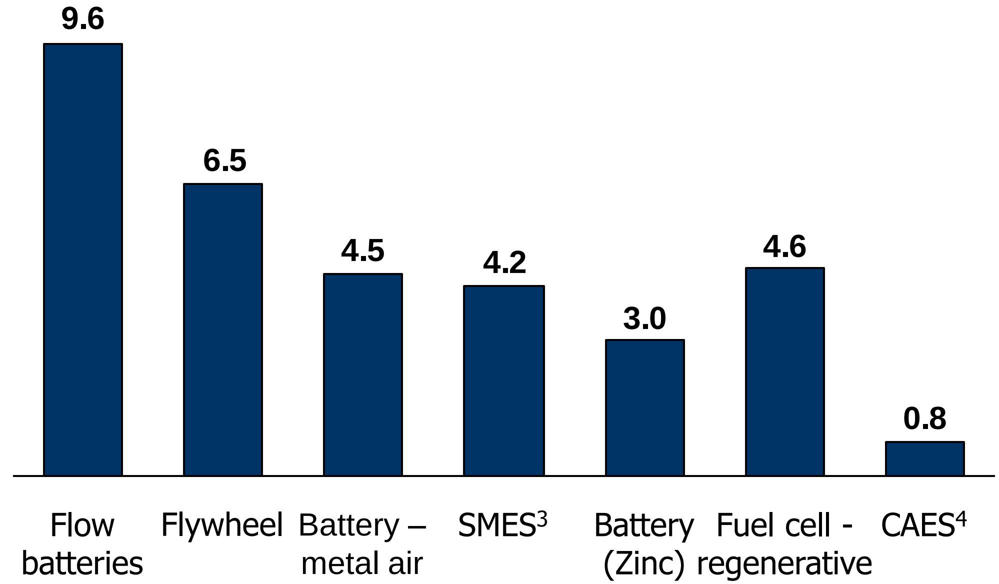
Source: European Commission Joint Research Center, "Annual Report 2011"; US Recovery & Reinvestment Act Website (www.recovery.gov)

CAES and batteries are receiving the prime share of DOE funding, whilst flow batteries are a promising future technology

DOE ELECTRICITY STORAGE GRANT DISTRIBUTION
$ million, 2009



DOE ARPA-E GRANTS FROM GRIDS[1] PROGRAM
$ million



US DOE granted $620 million through the ARRA[2] of 2009 to Smart Grid and Energy Storage projects around the country. $435 million went towards Smart Grids alone and the remaining $185 million to 16 utility-scale electricity storage projects.

The ARPA-E (Advanced Research Projects Agency-Energy) program of the DOE is dedicated to support "**high-risk, high-payoff**" rampable & dispatchable intermittent storage projects.

In February 2012 the **US DOE** announced that $120 million would be made available for research into batteries and electricity storage over the next five years.

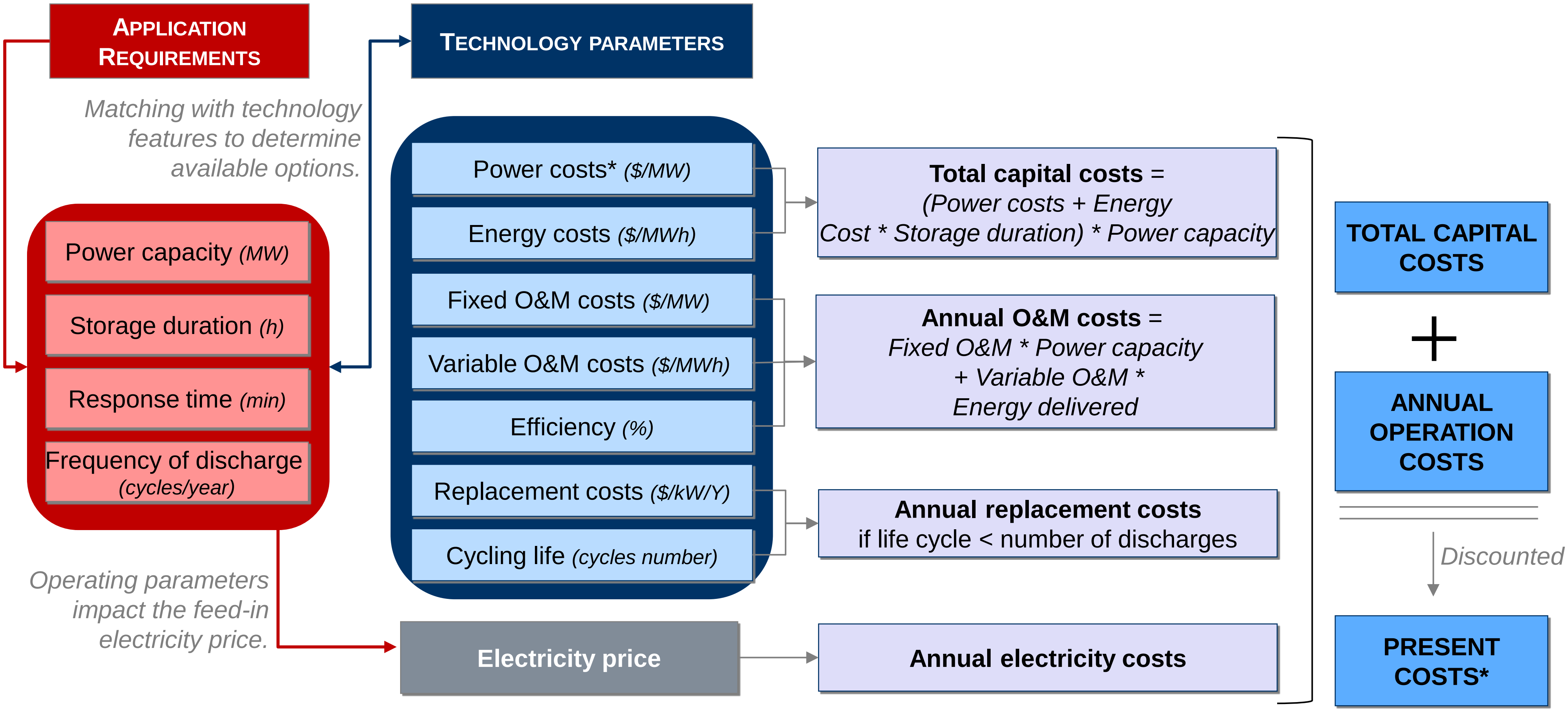
Note: [1] GRIDS: grid-scale rampable intermittent dispatchable storage; [2] ARRA: American recovery and reinvestment act; [3] SMES: superconducting magnetic energy storage; [4] CAES: compressed air energy storage.

Source: US Department of Energy (US DoE) website (http://www.energystorageexchange.org/projects)

4. Economics, financing & key players

The economics of electrical storage are affected both by technological features and applications, making them difficult to assess

STORAGE COSTS PARAMETERS

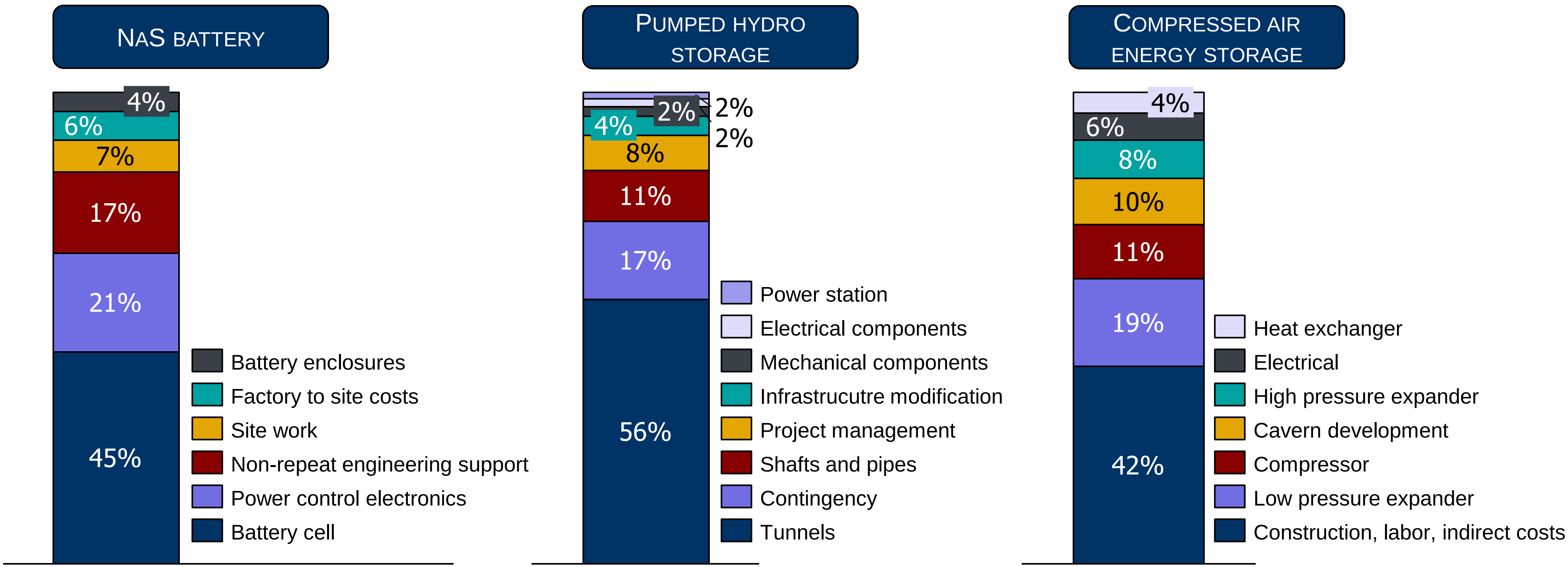


Note: * Power costs include storage device costs, balance of plant costs and power conversion costs.
** O&M: operation & maintenance except electricity price. Include gas price for compressed air energy storage.

Source: SBC Energy Institute Analysis

Capital cost breakdowns are technology-specific, with construction driving CAES and PHS costs, and components driving the cost of batteries

COST BREAKDOWN OF THREE STORAGE PLANTS
Percentage of unit of power ($/kW)

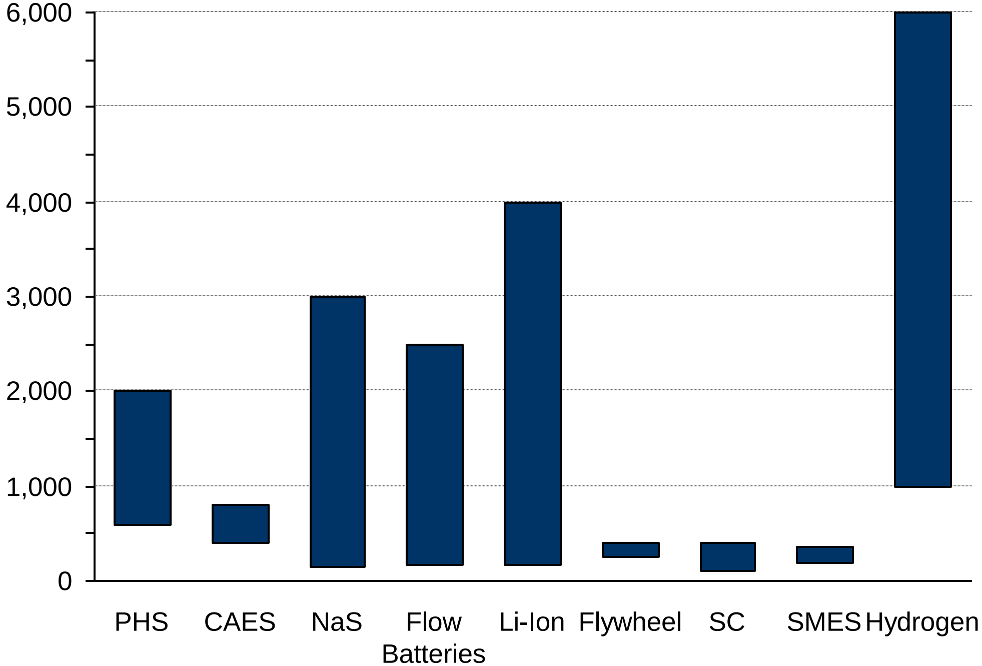


- Civil engineering works make up the bulk of pumped hydro storage (PHS) and compressed air energy storage (CAES) investment costs, but account for a negligible share of the initial investment in batteries.
- Cutting the capital costs of batteries will most probably involve using cheaper components (material, scale effect…), while pumped hydro storage or compressed air energy storage components may have to find cheaper sites or excavation techniques.

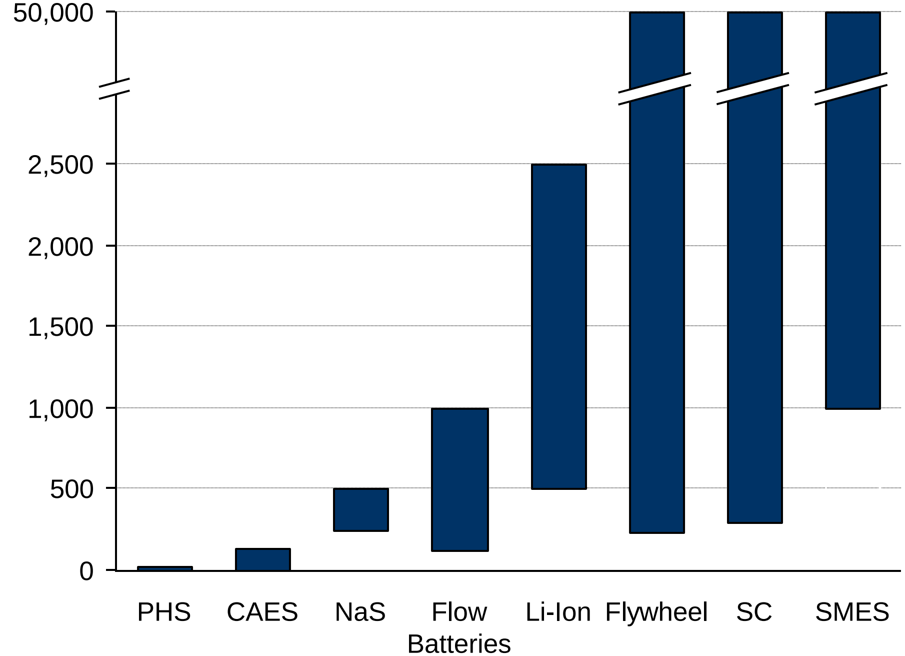
Source: Sandia (2007), “Installation of the first DESS at the American Electric Power”; Black & Veatch (2012), “Cost and performance data for power generation technologies”

The capital cost of a storage device per unit of power (MW) and per energy capacity (MWh) varies significantly between technologies

CAPITAL COSTS* PER UNIT OF POWER
$/kW



CAPITAL COST ** PER UNIT OF ENERGY CAPACITY
$/kWh



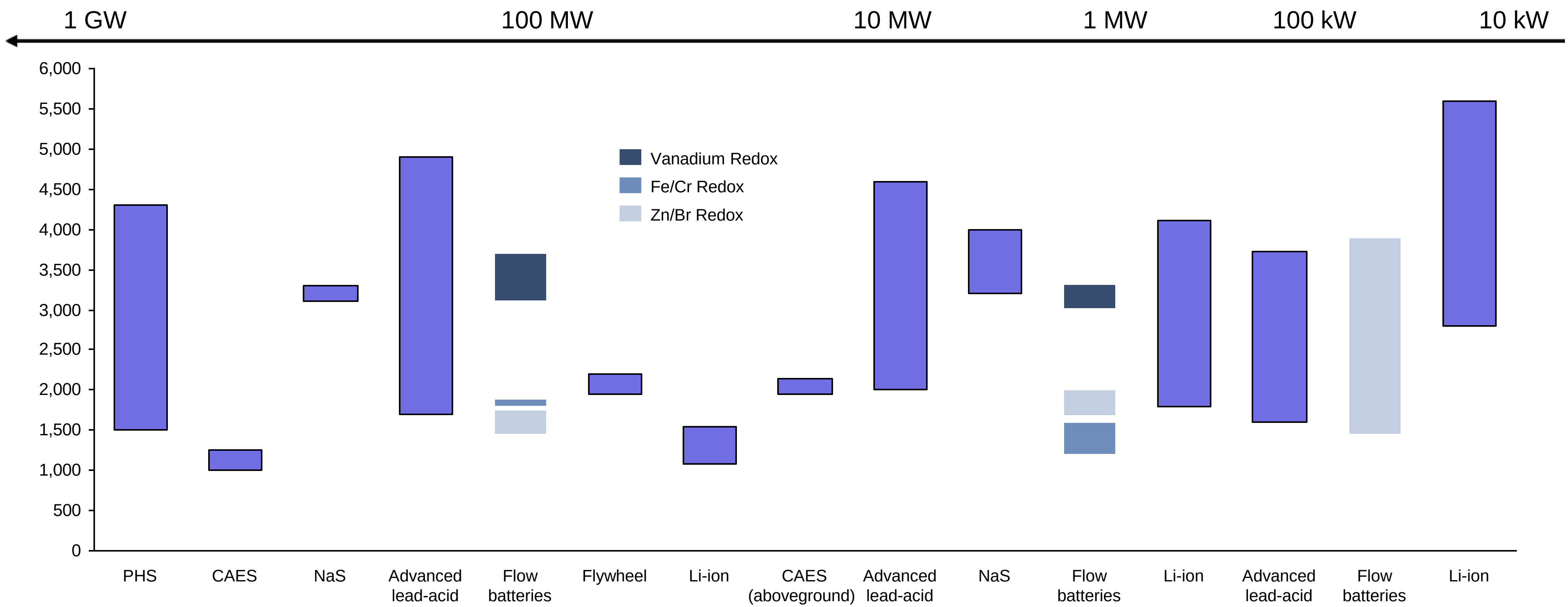
- Reflecting their advantage in power-driven storage applications, the cost per unit of power for flywheels, supercapacitors and SMES is relatively low compared with that of their competitors, though the cost per unit of energy is very high. The costs for pumped hydro, compressed air and batteries are more balanced, but the cost per installed power capacity of batteries varies widely.
- This division of costs may imply that power and energy capacities are independent, but this is not true for all systems. This is for example true for PHS, CAES and flow batteries but false for conventional batteries and flywheels.

Note: PHS: pumped hydro storage; CAES: compressed air energy storage; SC: supercapacitor, SMES: superconducting magnetic energy storage. Cost ranges are indicative and based on the high and low range of cost estimates provided in the literature. * They only take into account the cost of the storage device itself. ** Energy costs of flywheels, supercapacitors and SMES have been capped at $50,000/kWh but can be significantly higher.

Source: SBC Energy Institute Analysis based on

Total capital costs vary widely, depending on technology maturity and power capacity

ESTIMATES OF TOTAL CAPITAL COST BY TECHNOLOGY AND CAPACITY*
$/kW



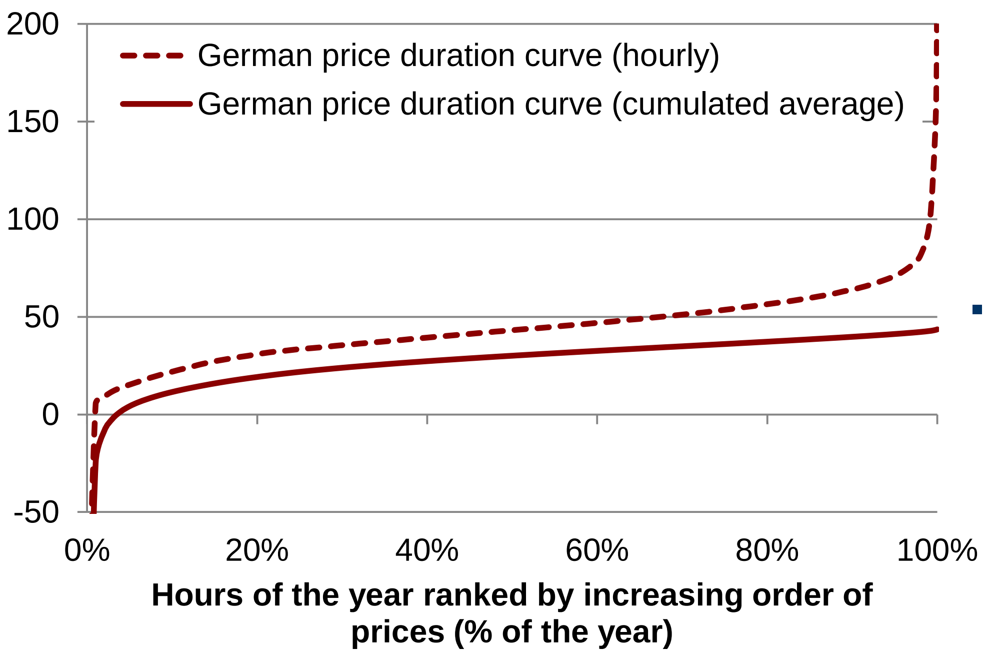
Storage duration (h)	6-10	8-20	6	4-6	5	0.25	0.25-1	5	3.2-4	7.2	4-5	2-4	2-5	2	1-4

Note: PHS: pumped hydro storage; CAES: compressed air energy storage; NaS: sodium-sulfur battery; Li-ion: lithium-ion battery; ZnBr: zinc-bromine; Fe/Cr: iron-chromium battery.
* Real costs are system and location-specific and these costs only give an order of magnitude.

Source: SBC Energy Institute Analysis based on EPRI (2010), "Electricity Energy Storage Technology Options"

Electricity prices and distribution patterns strongly influence storage costs

ELECTRICITY SPOT PRICE DURATION CURVES
€/MWh, 2012 in Germany



There is a trade-off between the cost of feed-in electricity and the utilization of plants to amortize the capital cost. Note that prices are negative during a few hours due to an excess of power from intermittent renewables and to the cost of shutting down non flexible baseload power plants.

- **The cost of storing electricity is composed of the price of the electricity** that is charged, stored and provided back to the grid*. Except for storage plants that are linked to generators that use "free" electricity, most plants purchase power on the spot market. Usually, storage plants try to store energy when electricity prices are low and redistribute it when prices are high. The electricity price distribution, depicted by the price duration curve, is consequently a key factor for storage economics.

- **However, the impact of the price of electricity on storage economics varies according to the end application**. For some applications, optimizing the buying and selling price is essential for price arbitrage, which takes advantage of the price spread of electricity. Intermittent balancing and power-fleet optimization are also highly dependent on the price structure, as the storage devices are likely to be charged when there is an over-supply of electricity and prices are low, and to be discharged when there is a shortage of electricity and prices are high. The price structure may be of lesser importance for applications that ensure power quality, defer grid investment or provide ancillary services, where revenues are not usually primarily obtained from selling electricity but rather from the remuneration of the services provided (*e.g.* black start, frequency regulation).

Note: * Compressed air energy storage also include the cost of the gas used upon decompression.
Source: EPEX SPOT Market Data 2012

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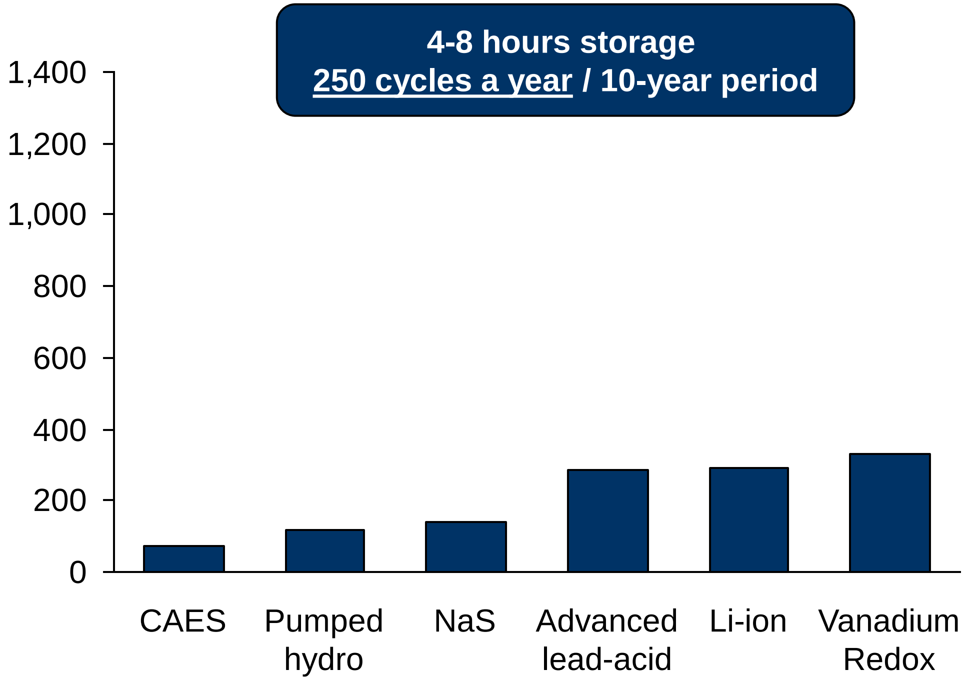
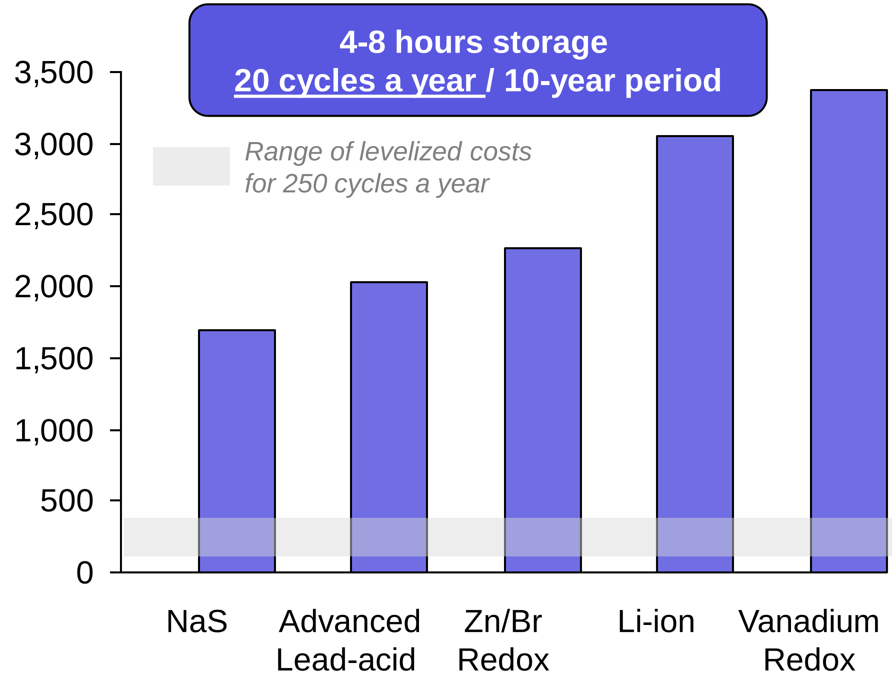
The full costs of electricity storage vary significantly, depending on applications, changing the competitive landscape among technologies (1/2)

LEVELIZED COSTS OF STORAGE* FOR TWO APPLICATIONS WITH SAME STORAGE DURATION
$/MWh





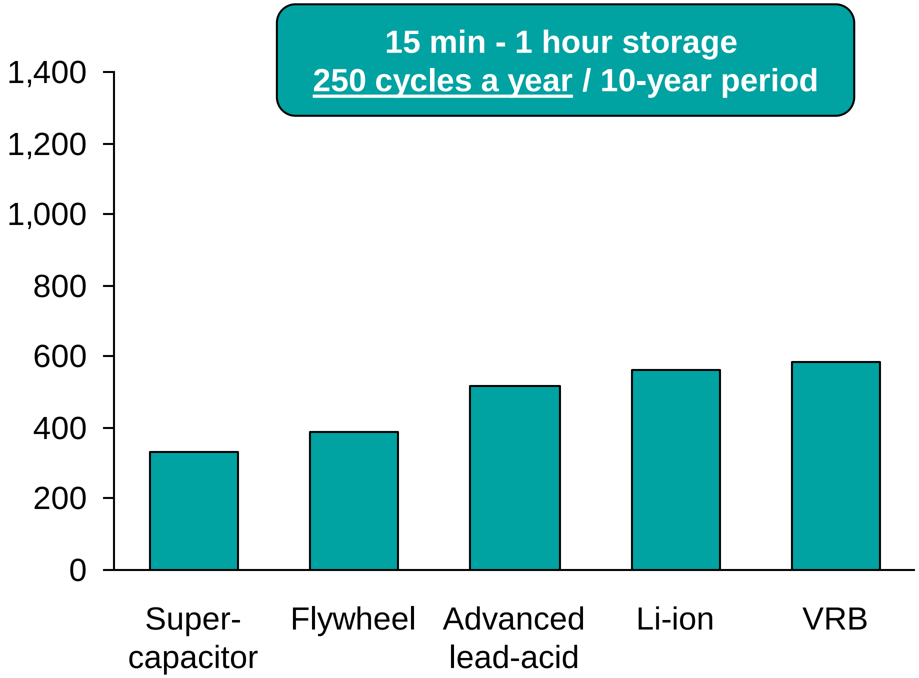
- Compressed air energy storage is the most cost-effective technology for frequent discharging (1 cycle every day for 250 days per year) over long durations (8 hours) such as is required by power fleet optimization applications or price arbitrage (store during the night and discharge during the day).
- For long-term storage with low cycling frequency (*e.g.* grid investment deferral on a line that suffers from occasional congestion), batteries with low capital requirements will be favored over those with a high cycling life. High capital-cost technologies cannot compete, nor can power-driven devices such as flywheels.

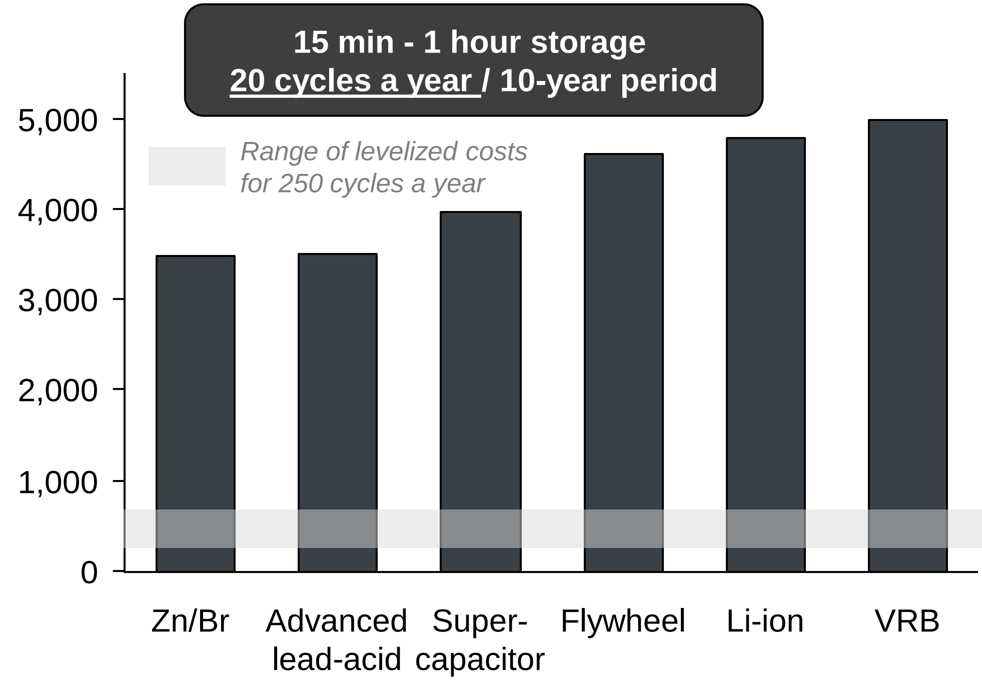
Note: * Levelized costs take into account discounted annualized operation costs as well as full capital costs. Assumptions about each technology can be found in the source document below.

Source: Sandia (2011), "Energy Storage Systems Cost Update"

The full costs of electricity storage vary significantly, depending on applications, changing the competitive landscape among technologies (2/2)

LEVELIZED COSTS OF STORAGE* FOR TWO APPLICATIONS WITH SAME STORAGE DURATION
$/MWh





- Technologies that benefit from a relative long cycling life (*e.g.* supercapacitors, flywheels) are favored over batteries for applications that require a high number of cycles (no replacement costs incurred over the 10-year period). High power capacity technologies (*e.g.* pumped hydro storage, compressed air energy storage) are not suited to short storage duration

- In case of a low number of cycles per year, batteries with the lowest capital costs per unit of power will be the most competitive.

Note: * Levelized costs take into account discounted annualized operation costs as well as full capital costs. Assumptions about each technology can be found in the source document below.

Source: Sandia (2011), "Energy Storage Systems Cost Update"

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Depending on the end-application, the benefits of storage can be difficult to monetize, making it more complicated to build a business case

APPROACHES TO ESTIMATING THE VALUE OF STORAGE

	APPROACH	CONCEPT
1	*Based on* MARKET PRICE	Revenues correspond to the price in markets where storage operators can bid (*e.g*. capacity market, frequency regulation market, black-start services). It also includes price-arbitrage applications
2	*Based on* AVOIDED COSTS	In the absence of a market, the benefits of electricity storage can be assessed implicitly by evaluating the costs avoided because of investment in storage (*e.g.* deferral of transmission & distribution investment, reduced transmission congestion charges…)
3	*Based on* COMPETING TECHNOLOGY / WILLINGNESS TO PAY	If electricity storage has an intrinsic value, it can be assessed by comparing alternative technologies (*e.g.* ensuring power quality for end-users, optimization of the power fleet by storing excess power from renewables instead of shutting down baseload power plants)

- The financial benefits of storage depend on the application and can be difficult to evaluate. *Market-based applications* generate revenues. Their business cases are therefore easier to assess using classic investment tools. However, they may be subject to uncertainty regarding frequency of use and price. *Avoided costs* are not very difficult to evaluate. The discounted cost of storage can be compared to avoided costs, including risk. Finally, the *"intrinsic"* value of storage is more complicated to assess. Willingness-to-pay suffers from "free-rider" behavior, while competing technology does not always exist*.

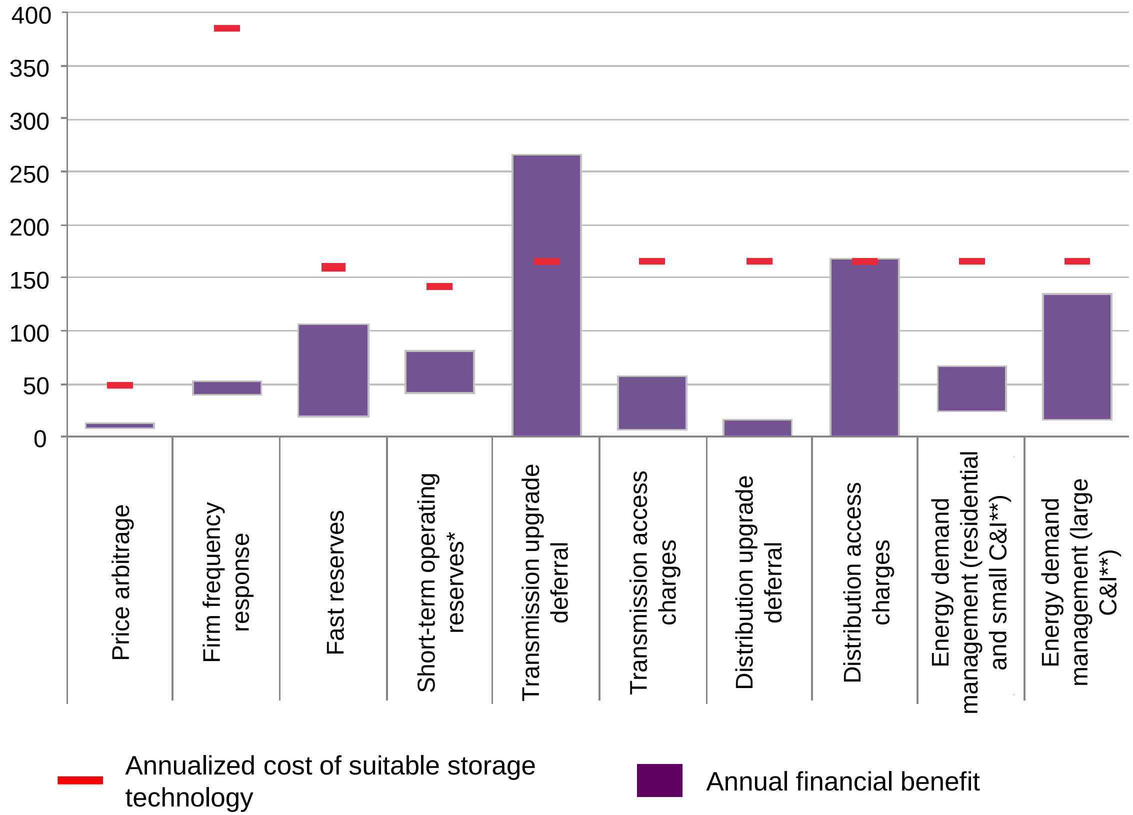
- Investors in storage may not necessarily be its main beneficiaries. Some benefits are social and cannot be allocated to specific players. Storage can also generate positive externalities than cannot be monetized in the absence of specific regulations.

- Regulation is likely to help determine the value of storage. Market rules must be put in place to ensure that storage can participate in the capacity market or other ancillary services. System operators should be incentivized to avoid costs, instead of using remuneration pegged to investment budgets. Regulators have to find the most efficient ways to allocate and share storage costs when their benefits are positive.

Note: * Free-riders refers to someone who benefits from resources, goods, or services without paying for the cost of the benefits.
Source: ISEA/RWTH Aachen (2012), "Technology Overview on Electricity Storage. Overview on the potential and on the deployment perspectives of electricity storage technologies"; ETH Zurich (2012), "Economics of Energy Storage"

Currently, the costs of electricity-storage applications outweigh the financial benefits

ANNUAL BENEFIT OF STORAGE APPLICATIONS IN THE UK COMPARED WITH ANNUALIZED COST
£/MWh-installed/year, Bloomberg New Energy Finance analysis



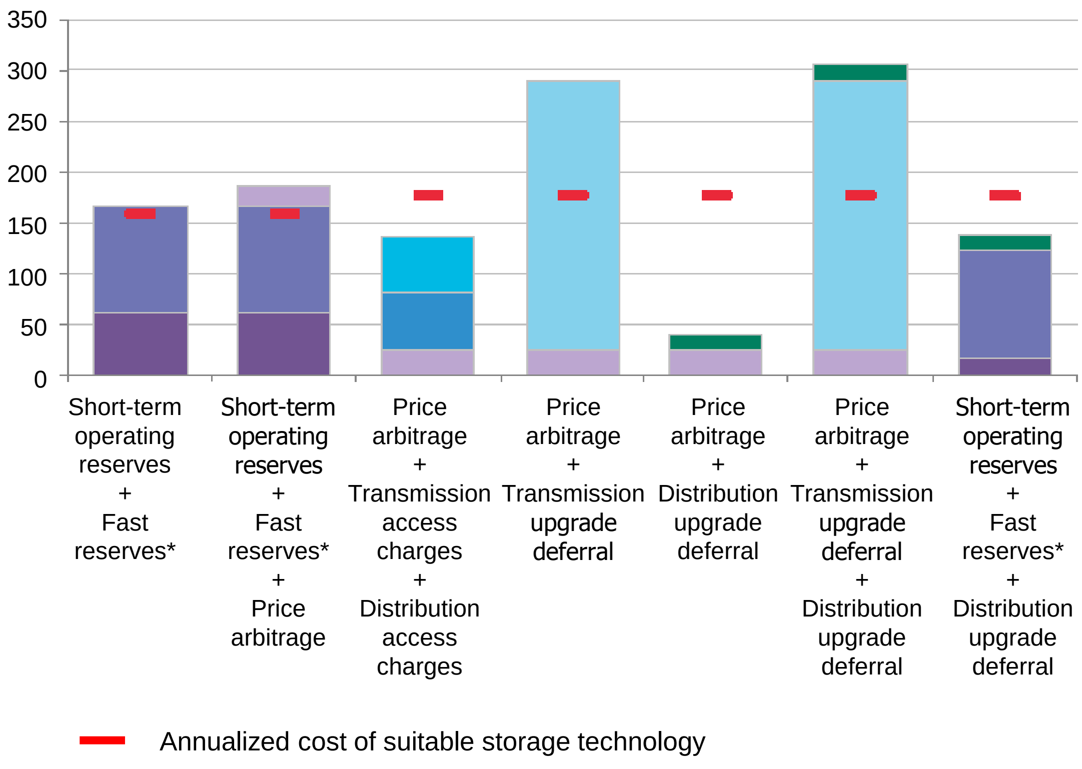
- Currently, individual electricity storage applications struggle to generate enough financial benefits to cover their costs. Bloomberg New Energy Finance (BNEF) simulates the current discrepancy between costs and revenues for the UK. According to BNEF analysis, the only activities that may achieve profitability in favorable conditions are the deferral of transmission upgrades and avoidance of distribution access charges.
- However, the results for the UK cannot be generalized to other systems. In Switzerland, price arbitrage applications of pumped hydro storage are believed to be profitable thanks to favorable natural conditions and access to cheap German electricity***.
- The struggle to achieve profitability results from technological maturity, regulatory barriers and from a poor utilization rate, making it difficult to amortize the high initial investment (*e.g.* price arbitrage can only be used when the spread is high enough to compensate for energy losses and other operating costs).

Note: * Short-term operating reserve.
** C&I: commercial and industrial.
*** This occurs in the case of high intermittent production (*e.g.* good windy day) and low demand (*e.g.* late at night).

Source: Bloomberg New Energy Finance (2013), "IEA Energy Storage Technology Roadmap Initial Stakeholder Engagement Workshop proceedings"

Bundling applications seem to be a strong lever in helping electricity storage become profitable

ANNUAL BENEFIT OF STORAGE APPLICATIONS IN THE UK COMPARED WITH ANNUALIZED COST
£/MWh-installed/year, Bloomberg New Energy Finance analysis



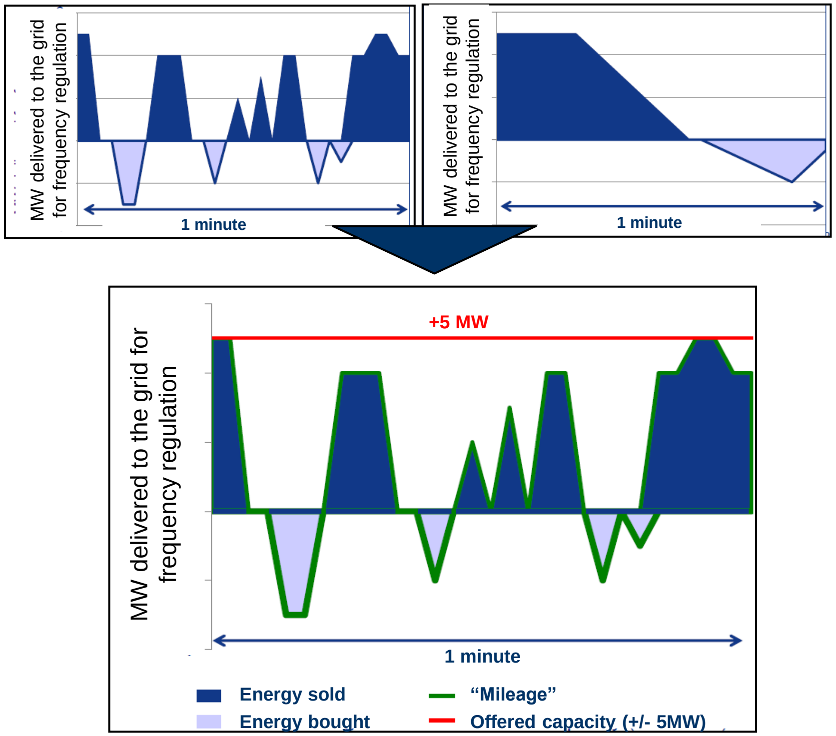
- Bundling applications is believed to help increase the utilization of storage plants and revenues. For instance, a very flexible storage plant can provide ancillary services over several different timeframes (fast reserves and short-term operating reserves – STOR), while taking advantage of price arbitrage when it can be achieved. According to a Bloomberg New Energy Finance analysis of the UK market, bundling could make several applications profitable (see graph opposite).
- Not all applications can be bundled and potential combinations have to be carefully assessed at the system level because of variations in regulatory frameworks and local specificities (demand curve, intermittency patterns…).
- Application bundling is challenging as its efficiency relies on very complex optimization models that are not yet commonly used and still necessitate further R,D&D. It may also be faced with regulatory barriers for ancillary services.

Note: * Fast reserve is part of the operating reserve (requires to provide at least 25 MW/min within 2 minutes and for 15 minutes).
Source: Bloomberg New Energy Finance (2013), "IEA Energy Storage Technology Roadmap Initial Stakeholder Engagement Workshop proceedings"

The regulatory framework will play a crucial role in enabling the monetization of the expected benefits of electricity storage

REGULATION "MILEAGE"*

Equal amounts of energy are provided by two assets over a specified time frame, leading to the same payment, even if the service is very different



Adding remuneration for the mileage as PJM did will help fast-response storage plants to valorize the service they are providing

- Market rules and regulatory frameworks affect the ability of developers to monetize electricity storage. Common barriers are:
  - **Ability to participate in ancillary services**: storage is not always eligible to participate in ancillary services (markets or bilateral agreements) nor to resource adequacy. This is particularly true for small capacity storage due to a minimum size required;
  - **Ownership of storage plant**: in several unbundled systems, storage is considered a production asset and system operators (transmission or distribution) are not allowed to own storage devices. This is a strong impediment to transmission and distribution deferral applications that are considered to be among the most promising revenue streams;
  - **Monetization of fast-response assets**: frequency regulation usually rewards MW withdrawn or injected to stabilize the grid without taking into account the speed of the response;
  - **Lack of cohesive, transparent and stable framework** increases investment risks.
- **Several solution are being investigated**:
  - Develop capacity markets with fair rules to allow the inclusion of storage;
  - Implement electricity storage procurement targets for utilities (as under consideration by the California Public Utilities Commission);
  - Promote regulation "mileage" like PJM did in the US (see graph opposite - Clean Horizon Consulting ©).

Note: *Copyright© Clean Horizon Consulting (2012), "Financing hydrogen: focus on an additional value stream"
Source: Joseph Eto (2012), "Renewable Electricity Policies in the US and a Status Report on California's Energy Storage Procurement Target"; EASE / EERA (2013), "European Energy Storage Technology Development Roadmap Towards 2030"

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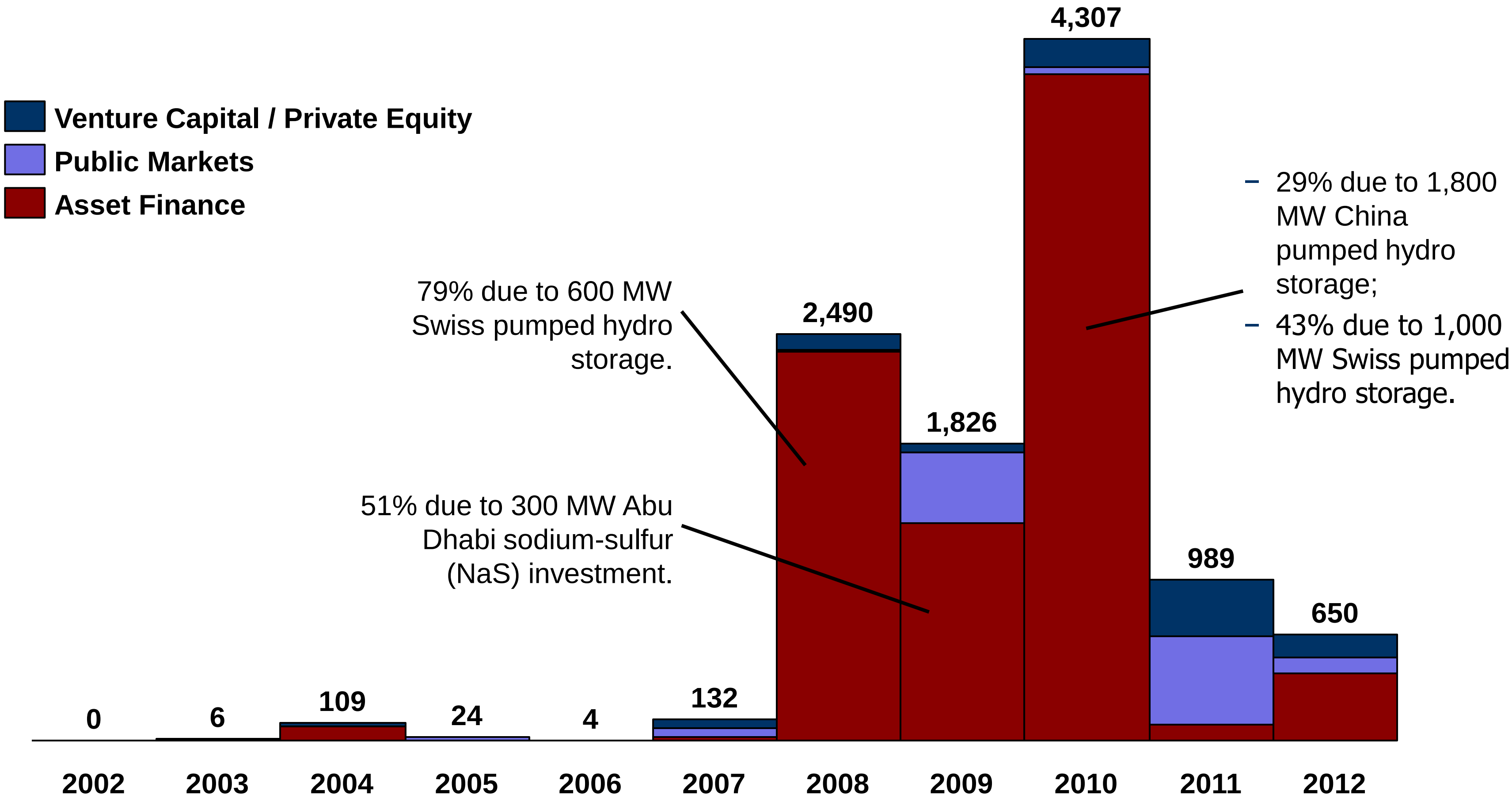
Although tending to increase, year-on-year investment levels can be erratic and can be dependent on single projects such as power sams storage facilities

TOTAL INVESTMENT IN ELECTRICITY STORAGE

$ million



Note: PHS: pumped hydro storage.

Source: SBC Energy Institute Analysis based on Bloomberg New Energy Finance database extracted on 12th April 2013

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The electricity storage sector is fragmented by technology and composed of small players focused exclusively on storage and large companies diversifying

MAIN ACTORS OF ELECTRICITY STORAGE

Pumped hydro storage	CAES	Flywheels	Hydrogen & synthetic natural Gas	Batteries	SMES & capacitors
- China Southern Power Grid - China hydroelectric - Duke energy - Gridflex energy - Emera - Ukrhydroenergo - First hydro company - IMPSA - Voith hydro - Alstom Power	- Gridflex Energy - SustainX - General Compression - Energy Storage & Power - Energy Systems & Power Consultants - Lightsail - E.ON	- Beacon Power - Vycon - Amber kinetics - Active Power - Temporal Power - Toshiba	- Hydrogenics - ITM Power - Ballard - Siemens - McPhy - SolarFuel - NEL - Air Liquide - SunFire - Giner - Linde - Areva - Electrochaea - E.ON - Proton On Site	- ABSL - Altair nanotechnologies - Battery Systems - Tianjin Lishen Battery - Byd Co - Ashlawn Energy - Redflow Technologies - ZBB Energy - Prudent Energy - Exide Technologies - NGK Insulators - Kokam - Ecoult	- Maxwell technologies - NEC - American Superconductor

Note: CAES: compressed air energy storage; SMES: superconducting magnetic energy storage.
Source: SBC Energy Institute Analysis based on Bloomberg New Energy Finance database

5. Environmental & social impacts

The environmental impact of storing energy is difficult to evaluate

IMPACT CATEGORISATION

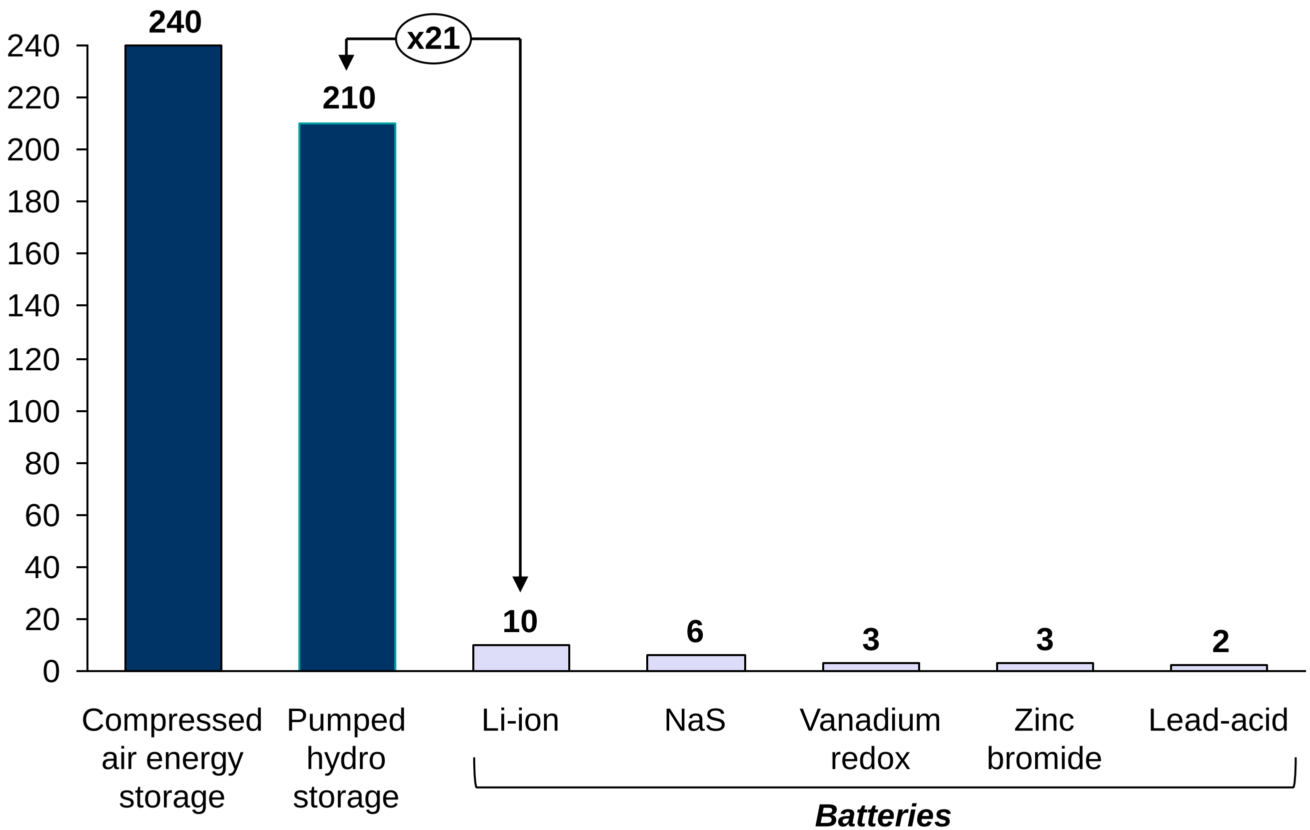
Impact categorisation	**GHG* emissions**	**Land use**	**Water use**
Direct	No GHG emissions except conventional CAES**	Depends on energy density & power density of storage technologies	Can be high for Conventional PHS*** & CAES**
Lifecycle: *Construction*	Depends on the energy intensity and the way it is produced. Some issues with batteries	Depends on the energy intensity and land use during construction. No major issues	No major issues outside CAES** salt caverns construction
Lifecycle: *Operation*	Depends on storage efficiency and GHG emissions of upstream energy	Depends on land footprint of electricity stored and storage efficiency	Depends on water use of electricity stored and storage efficiency
Induced	**Positive**: − Maximize intermittent renewable or nuclear production; − Avoid using peak power plants. **Negative**: − Increases energy losses in the system (to be compared on a lifecycle basis with alternative solutions).		

- As with "smart energy technologies" such as smart grids or demand-side responses, the environmental impacts of electricity storage are difficult to evaluate. They are a function of the storage technology's direct impact, but also of the impact of the upstream source of electricity used for charging, of the electricity displaced upon discharging, and of the increase in generation needed to balance storage losses.
- The environmental impact of storage is not restricted to air pollution and GHG emissions, but also encompass water requirements and land use.
- In some cases, electricity storage can change the emissions intensity of the power mix (*e.g. for instance,* charge by night with coal and discharge during the day, instead of using gas turbines).

Note: * GHG: greenhouse gas; ** CAES: compressed air energy storage; *** PHS: pumped hydro storage.
Source: SBC Energy Institute Analysis; NREL (2012), "Renewable Electricity Futures Study – Volume 2: Renewable Electricity Generation & Storage Technologies"

Recent studies suggest batteries are difficult to deploy as a large-scale storage solution because of their high energy intensity

RATIO OF ELECTRICAL ENERGY STORED IN THE LIFETIME OF THE STORAGE DEVICE TO ITS EMBODIED PRIMARY ENERGY
MJ/MJ



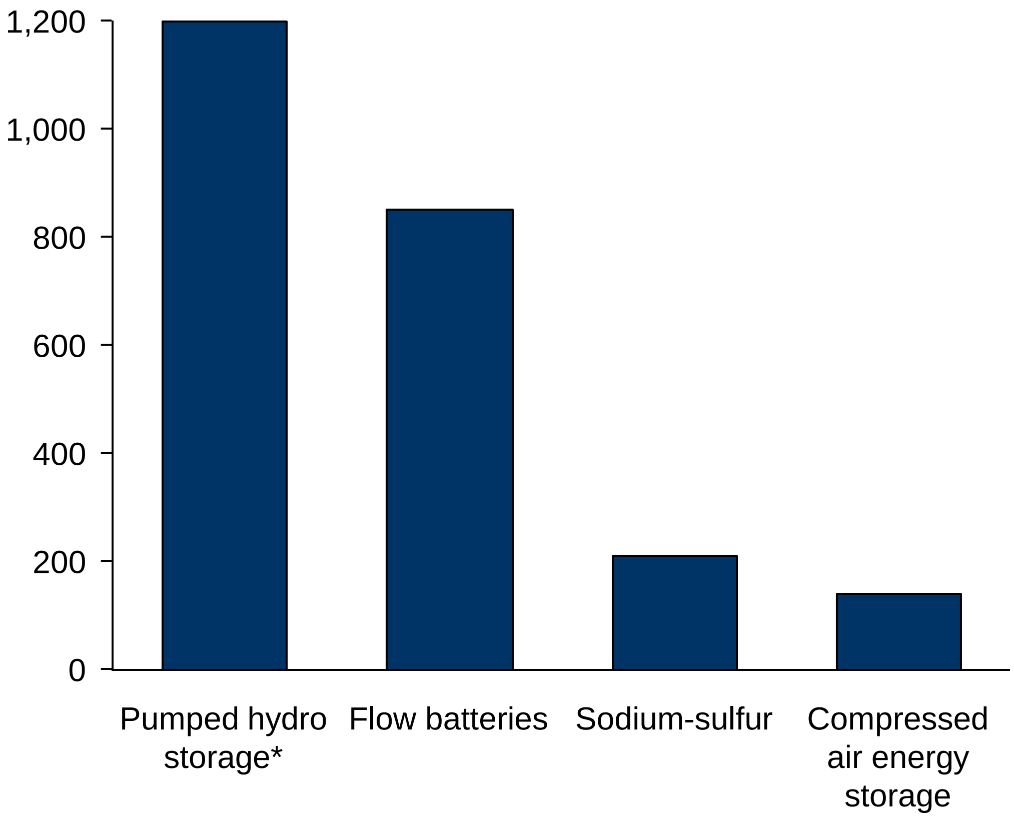
- Pumped hydro storage (PHS) and compressed air energy storage (CAES) plants are on average less energy intensive than electrochemical storage (batteries) by a factor ranging between 21 and 120.
- This is mainly a result of the short cycling life of batteries, but also from the material of which they are made. Unlike PHS and CAES, batteries tend to rely heavily on certain metals that need to be mined and transformed.
- Although R&D is currently mainly focusing on increasing energy and power density, it seems that improving the cycling life of batteries could greatly reduce their environmental impact, as well as their capital cost.

Note: The graph displays the ratio of electrical energy stored over the lifetime of a technology to the energy needed to build it. Stored energy over the lifetime depends significantly on the cycling life, the efficiency and the depth of discharge.

Source: Charles J. Barnhart (2013), “On the importance of reducing the energetic and material demands of electrical energy storage”

Pumped hydro storage uses extensive amounts of land and raises social acceptance issues

LAND USE BY TECHNOLOGY
m²/MW

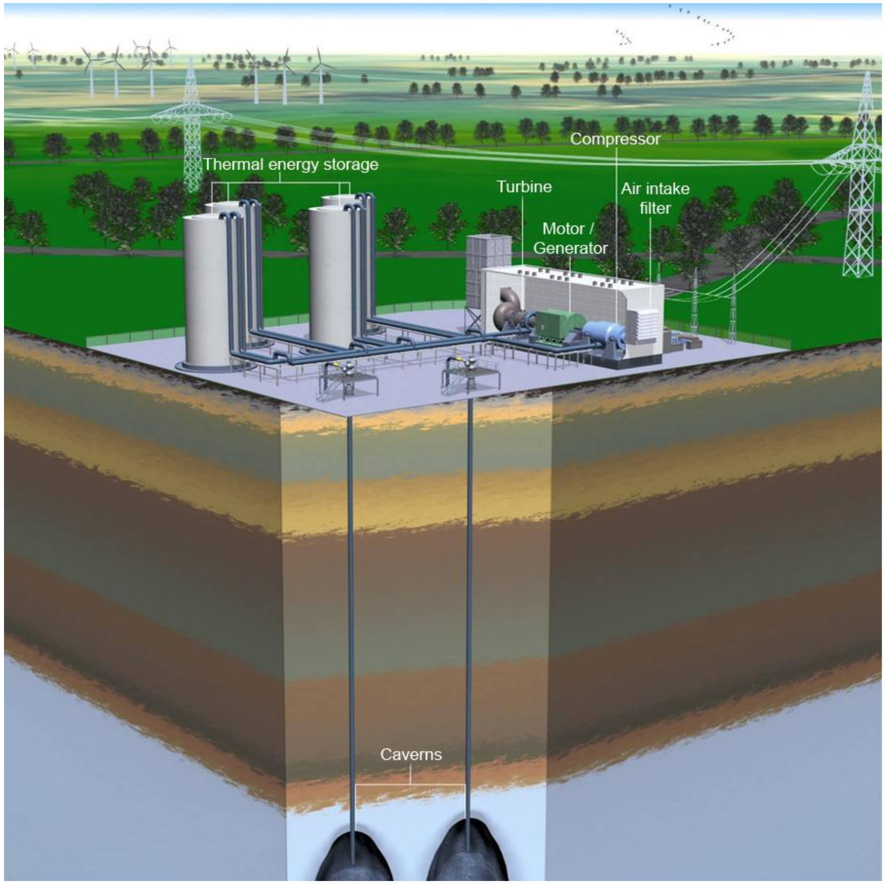


- **Pumped hydro storage (PHS) has a high land footprint** due to its poor energy density (1 cubic meter of water over a height of 100 meters gives 0.27 kWh of potential energy). The footprint depends to a large extent on the nature of the reservoirs and the date of construction. According to the National Renewable Energy Laboratory, the total flooded area of old plants with man-made upper and lower reservoirs can exceed 4,000 m²/MW, while more recent projects have significantly lower land requirements that average around 1,200 m²/MW.
- **PHS requires a substantial volume of water**. For example, a 1,300 MW closed-cycled facility would require 3 billion liters per year, or 1.1 liter/kWh, mainly due to evaporation. Pumping can disrupt the local environment by increasing the temperature (affecting water quality and aquatic life) and trapping aquatic life in the system.
- **Construction will impact the local ecosystem, wildlife, and modify the landscape** by blocking the natural flow of a river or flooding a previously dry area.
- **Developers are looking to avoid these environmental impacts** by using seawater, underground PHS or recycled wastewater.

Note: * Pumped hydro storage footprint refers to recent projects.
Source: SBC Energy Institute Analysis based on NREL (2012), “Renewable electricity futures study”

Although compressed air energy storage (CAES) uses very little land, it is associated with greenhouse gas emissions and high water consumption

RWE ADELE ISOTHERMAL CAES PROJECT



- **Conventional compressed air energy storage (diabatic CAES) requires fuel to heat up the compressed air upon decompressing**, for which it usually relies on natural gas. Therefore, CAES causes air pollution, mainly in the form of nitrogen oxide (NOx), and also emits carbon dioxide (CO_2), in amounts roughly equivalent to only one-third emitted from a conventional gas turbine with the same power rating, *i.e.* around 100 grams and 150 grams per CO_2eq./kWh. Recent projects (EPRI 2012) focus on reducing emissions using a loop that uses exhaust gas to heat up the air.
- **Conventional CAES (diabatic) requires high volumes of water to cool down the compressed air before storing it**. It is estimated that a 2,700 MW facility would use almost 3.5 billion liters of water every year for this purpose, or 0.75 liter/kWh. Furthermore, if the air is stored in man-made salt caverns, water will be needed to dissolve the salt formation (about 8 m^3 for each cubic meter excavated). This will also result in large quantities of brine, which will need to be disposed of.
- **Developing adiabatic and isothermal technologies* could significantly reduce the environmental impact** of CAES by avoiding the need for external fuel and decreasing water requirements.

Note: Refer to the R,D&D section on CAES for more information on adiabatic and isothermal concepts.
Source: NREL (2012), "Renewable electricity futures study"; RWE (2010), "ADELE – adiabatic compressed-air energy storage for electricity supply"

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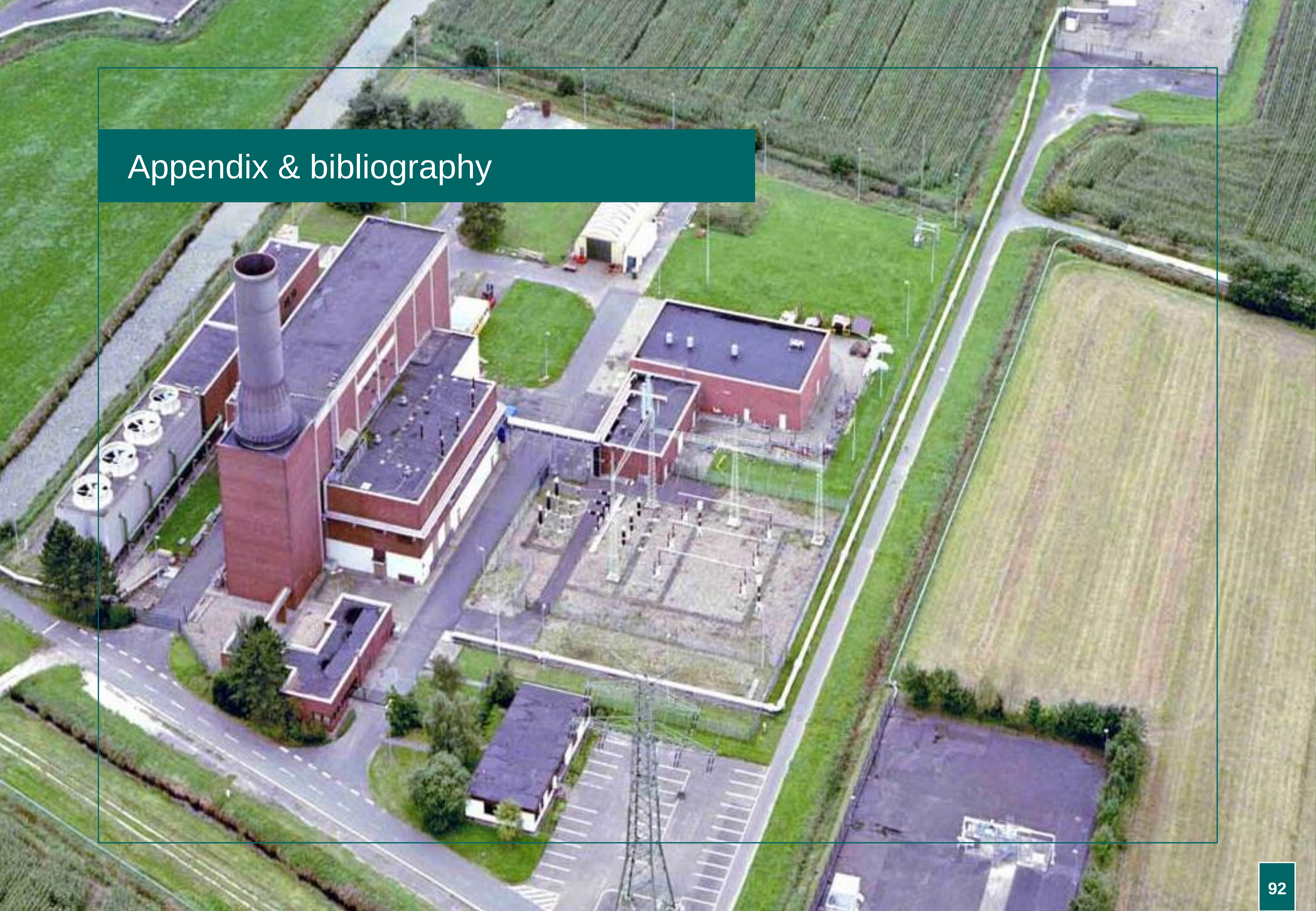
Appendix & bibliography



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Acronyms

- **AC**: Alternative Current
- **A-CAES**: Adiabatic Compressed Air Energy Storage
- **ARPA-E**: Advanced Research Projects Agency-Energy
- **ARRA**: American Recovery and Reinvestment Act
- **BNEF**: Bloomberg New Energy Finance
- **CAES:** Compressed Air Energy Storage
- **CAPEX**: Capital Expenditures
- **CO_2**: Carbon dioxide
- **CSP:** Concentrating Solar Power
- **DC**: Direct Current
- **DoE:** Department of Energy
- **DSO**: Distribution System Operator
- **EV**: Electric Vehicle
- **GHG**: Greenhouse Gas
- **H_2**: Hydrogen
- **Hz:** Hertz
- **IEA**: International Energy Agency
- **kWh**: kilowatt hour
- **Li-ion**: Lithium-ion
- **LA**: Lead-acid
- **Mg**: Magnesium
- **ms**: milli-second
- **MSES**: Molten Salt Energy Storage
- **NaS**: Sodium-sulfur
- **NSW**: New South Wales
- **NiCd**: Nickel Cadmium
- **OPEX**: Operational Expenditure
- **O&M**: Operation and Maintenance
- **P2G**: Power-to-Gas
- **PCM**: Phase Change Material
- **PHS**: Pumped Hydro Storage
- **PJM**: Pennsylvania-New Jersey-Maryland
- **PV**: Photovoltaic
- **R,D&D:** Research, Development & Demonstration
- **SC**: Supercapacitor
- **SNG**: Synthetic Natural Gas
- **SMES**: Superconducting Magnetic Energy Storage
- **SVC**: Static VAR Compensator
- **T&D**: Transmission & Distribution
- **TSO**: Transmission System Operator
- **UHVDC:** Ultra High Voltage Direct Current
- **VRB**: Vanadium Redox Batteries
- **W**: Watt
- **Zn/Br**: Zinc-bromine

Picture credits

- **Slide 10, 34**: Rokkasho-Futumata 34 MW sodium-sulfur (NaS) battery storage system, Japan, NGK
- **Slide 20**: Linthal pumped hydro storage (PHS) 1,000 MW expansion project, Switzerland, Axpo Group
- **Slide 27, 48**: Seneca 435 MW pumped hydro storage plant in Pennsylvania, USA, FirstEnergy
- **Slide 29, 92**: Huntorf 290 MW compressed air energy storage (CAES) plant, Germany, E.ON
- **Slide 31**: Stephentown 20 MW flywheel storage plant, US, Beacon Power
- **Slide 35**: Laurel Mountain 32 MW lithium-ion (Li-ion) battery storage system, US, AES Energy Storage
- **Slide 37**: Gills Onions 600 kW vanadium redox battery system, US, Prudent Energy
- **Slide 39**: Palmdale 450 kW supercapacitor, US, Maxwell Technologies
- **Slide 41**: Superconducting magnetic energy storage demonstrator, CEA Training
- **Slide 43**: Molten salts storage tanks in Andasol 150 MW concentrating solar plant (CSP), Spain, Solar Millennium/ACS Cobra
- **Slide 45**: Hybrid power plant including 500 kW electrolyzer, Germany, Enertrag
- **Slide 47**: Power-to-gas 250 kW Alpha Plant, Germany, ZSW / Etogas
- **Slide 60**: Pumped hydro storage tunnel boring machine, Switzerland, Axpo Group
- **Slide 72**: San Jose 500 kW fuel cells eBay installation, US, Bloom Energy
- **Slide 86**: Bluffton 2 MW sodium-sulfur (NaS) battery storage system, US, S&C

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September 2013

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